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NEW APPROACHES TO MOTION CUING IN FLIGHT SIMULATORS (U)

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FOR THE COMMANDER

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A study was conducted to investigate new approaches in motion simulation. The study developed a conceptual model of pilot control of an aircraft which was subsequently used in a "need-based" analysis of motion cuing devices. The analysis technique involved a frequency domain representation of aircraft maneuvers, pilot perception of these maneuvers, and pilot perception of the cues from various simulator cuing devices. The analysis led to an assessment founded upon principles of pilot perception and behavior. An analysis task was performed on a pop-up attack in an F-4 aircraft to generate the aircraft maneuver time histories and pilot cue matrix. The results were used in a frequency domain analysis to determine the value of cuing devices for particular portions of the maneuver. The study investigated various cuing techniques beginning with proposed optimization of existing devices and proceeding to discuss several new techniques such as vibromyesthetic stimulation and direct electrical stimulation of nerves and muscles. The report concludes with recommendations for (1) future work employing the newly developed analytical technique and (2) experimentation with selected new devices to determine their cuing value.

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Summary

A study was conducted to investigate new approaches in motion simulation. The study developed a conceptual model of pilot control of an aircraft. This model was subsequently used in a "need-based" analysis of motion cuing devices. This analysis technique involved a frequency domain representation of aircraft maneuvers, pilot perception of these maneuvers and pilot perception of the cues from various simulator cuing devices. The analysis led to an assessment founded upon principles of pilot perception and behavior.

A task analysis was performed on a pop up attack in an F-4 aircraft to generate the aircraft maneuver time histories and pilot cue matrix. The results of this task analysis were used in a frequency domain analysis to determine the value of cuing devices for particular portions of the maneuver.

The study investigated various cuing techniques beginning with proposed optimization of existing devices and proceeding to discuss several new techniques such as vibromyesthetic stimulation and direct electrical stimulation of nerves and muscles.

The report concludes with recommendations for (1) future work employing the newly developed analytical technique and (2) experimentation with selected new devices to determine their cuing value.

Preface

This study was completed under a subcontract to Systems Research Laboratories (SRL) in support of the Armstrong laboratory, Wright-Patterson Air Force Base, Ohio. The technical monitor for this subcontract was Matt Middendorf of SRL.

The authors acknowledge the valuable contributions of Major Ed Billman, Mr Matt Middendorf, Dr John Flach, Wright State University Major Bill Ritter, and Stephen Hottman, SRL.

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1.0 Introduction

1.1 The Problem of Motion Cuing in Flight Simulation

The problem of designing a flight simulator which can provide realistic motion cues to the pilot has challenged the industry from its very earliest days. Ed Link's great accomplishment in developing the original "Link Aviation Trainer No. 1" in 1924 lay in the use of pneumatics to provide three degrees of motion freedom in direct response to cockpit flight control inputs. The trainer, which was intended for primary flight training, allowed the student to see the effects of control inputs as the cockpit assembly reproduced aircraft attitude changes in heading, pitch and roll. It was fortunate for Link, however, that at low accelerations the human visual system provides very compelling perception of orientation and motion because the motions of the trainer, although nearly correct visually, provided largely incorrect forces and accelerations on the pilot. Consequently, the pilot's somatosensory and vestibular perceptions were unfaithful to the motions being simulated. When the Army, in 1936, began using Link's famous "Blue Box" for instrument training, the problems became more apparent: the pivot point was below the cockpit rather than at the simulated aircraft CG, and the simulator roll motions made even the most perfectly coordinated turn feel like a slip. In spite of the tremendous contribution that Link Trainers were making to pilot training, by the end of the war the government was specifying instrument trainers without motion systems.

Even today, the modern six-post motion system receives mixed reviews from users. No motion system can possibly reproduce the large sustained accelerations produced by combat aircraft, so just in the regime where force and motion cuing becomes dramatically significant to aircrew performance and training, elaborate motion platform technology seems to fail. Although motion platforms have proven their worth in helicopter simulators and in some transport simulators, the Air Force still prefers to avoid them for fighters. The F-16 simulator, for example, has no platform motion system. Barring an unforseen revolution in the technology of force and motion cuing, it is evident that it is hopeless to attempt to provide realistic force and motion stimuli in the sense that the acceleration forces produced by the aircraft can be replicated in the simulator. Sustained acceleration is not possible without sustained displacement, and any attempt to simply apply whole body acceleration forces directly will always require inappropriate counter forces. The key to circumventing this dilemma is to recognize that what matters in simulation is not the physical reality of the force and motion stimuli, but the perceptions associated with force and motion and the behaviors those perceptions elicit. The simulator is not called upon to replicate the motions of the aircraft, but rather to replicate the aircrew's perceptions associated with

that motion. Current practice in motion cuing with hydraulic platforms utilizes this approach to some extent by providing critical onset cues followed by subliminal washout, and by using "gravity align" platform attitudes to simulate some aspects of sustained acceleration. Nevertheless, motion platforms use actual acceleration to stimulate the pilot's sensation of acceleration; a more direct example of the synthetic stimulus technique is the g-seat--such as that used in the F-16 simulator. The g-seat provides no acceleration and exerts no forces, but rather simulates the sensation of g-induced buttocks and back pressure through changes in seat area and firmness. The device simulates acceleration-induced postural changes by adjusting seat orientation. The result is a psychological suggestion to the pilot of acceleration forces, which he interprets as being due to aircraft motion.

In pursuing this avenue of simulator design, two related questions emerge. The first is the availability of techniques for providing stimuli which can be interpreted by the human perceptual systems as force and motion cues. The second is the relevance of each of the various stimuli which are present in the real-world environment. Clearly, if a great deal of effort is to be expended in searching for and implementing force and motion analogs or stimuli which produce effects similar to those due to acceleration, the designer will be interested in identifying only those which are relevant to aircrew performance and training. In order to characterize candidate techniques on the basis of need, the designer must analyze the entire stimulus-response chain from the original aircraft maneuver through the physical stimuli provided to the pilot, through the physical responses of the human sensory receptors which detect the stimuli, and finally to the perceptual effects which elicit the behaviors resulting in the pilot's specific performance. In order to characterize candidate techniques on the basis of effectiveness, empirical studies on human subjects are clearly necessary.

While the invention and development of new techniques for expanding the cuing repertoire of simulators is clearly necessary, it is equally important to avoid the expense of providing cuing technology which is not relevant to pilot performance. All possible motions of the aircraft are not necessarily relevant to simulation: some areas of the performance envelope of the aircraft are never exercised; some stimuli are not detected by the human; and some perceptions are not relevant to performance. A critical task of the simulator designer is to identify those regimes of motion, sensation, perception, and behavior which are relevant to pilot performance, and then to devise techniques for producing--by synthetic stimuli--the appropriate range of pilot perceptions and behavior.

1.2 Objectives of the CUMOD Study

The study described in this report is the first phase of an effort to develop guidelines for the design of new force and motion cuing devices. The program has come to be called "CUMOD" because of its three long-term objectives.

1. Develop a suite of experimental Cuing Modules which advance the state of the art in flight simulation force and motion cuing and which utilize methods supported by a set of explicit scientific principles.

2. Perform experiments to validate the concepts employed, explore the effectiveness of the new technology, and advance our knowledge of motion perception.

3. Prepare guidelines and specifications for operational cuing devices utilizing the techniques developed under CUMOD.

This report comprises the results of the first phase of the program. The primary objective of Phase I was to establish the principled basis for the module development and for the experimental programs to be carried out in later phases. Specifically, Phase I had three objectives:

1. Research the scholarly literature on the psychophysiology of motion perception, the role of motion cues in piloting, the state of the art in simulator motion cuing, and the availability of novel technologies for stimulating motion perceptions.

2. Develop a scientific method for identifying and establishing the relevance of the force and motion cues used by pilots.

3. Identify promising new cuing technologies, study their applicability, and propose experimental investigations of the most promising candidates.

The CUMOD Phase I study addressed three areas. First were the types of motions the aircraft undergoes as it flies real maneuvers based on typical mission scenarios. Second were the modes of energy coupling to the aircrew: how does aircraft motion stimulate the sensory and perceptual systems of the aircrew? This question goes beyond simple reaction forces due to acceleration and extends to secondary stimuli such as g-suit inflation. It also addressed the question of how physiological effects on the aircrew manifest themselves in sensations, perceptions and constraints on action. Third were the psychophysical processes themselves: how do the characteristics

of the human physiological and perceptual systems affect the information inherent in the stimuli provided by the physical environment? It is wasteful to develop technology to provide stimuli which, although present in the environment, are not appreciated by the human organism or which otherwise do not affect pilot performance.

1.3 Methods Employed in the Study

The objective of the CUMOD project as a whole is to develop technology for improving the simulation of force and motion effects. It is a requirement of the program, however, that each proposed cuing technique rest on a scientific, principled basis. In order to direct the overall effort on these terms, the Phase I study was devoted largely to developing an analytical tool for identifying and characterizing the types of stimuli that are important to treat and the methods which could be used effectively to produce them in a simulator.

This effort began with a search of the scholarly literature. The literature search covered three main areas of knowledge and current research:

1. Human sensory, perceptual, and physiologic responses relevant to force and motion stimuli. This area was further decomposed by physiologic subsystem:

   a. Visual
   b. Vestibular
   c. Somatosensory
   d. Auditory
   e. Respiratory
   f. Cardiovascular
   g. Posturographic

2. Pilot control strategies and the pilot's use of motion cues.

3. Devices and techniques for stimulating sensory responses, measuring sensory function, and producing meaningful simulator force and motion cues.

The search concentrated on works produced since 1975, since a bibliography by Kron, Cardullo, and Young (1980) had already covered references up to that date. The search was conducted by conventional means including automated searches using the services of MEDLINE, DIALOG, and DTIC. The results of the literature study are compiled in a bibliography, which may be found in Appendix A.

The next problem was to devise a method of analyzing the motion cuing process and characterizing the need for and the effectiveness of synthetic motion cues in flight simulation. The approach adopted was to apply the techniques of linear analysis to the entire path of information flow from the motions of the aircraft through to the nervous outputs of the pilot's sensory systems. By graphically presenting the signals and subsystem transfer functions in the frequency domain, the regions of the motion spectrum excited by the piloted aircraft and appreciated by the pilot are presented clearly and quantitatively. A similar analysis applied to proposed cuing devices reveals explicitly the relationship between the actual and synthetic sensory stimuli in the context of flight. The analytic technique involves identifying the motions typical of operational flight maneuvers and then characterizing the pilot's sensory response to the resulting accelerations and forces in the frequency domain. The analysis effectively integrates the relevant effects of mission profile, aircraft response, pilot sensory system response, and simulator cuing device performance into a unified graphical presentation. This analytic method is described in detail in Section 3 of this report.

Frequency domain analysis of signal flow requires that the spectrum of the input signal and the transfer functions of all processing stages be known. Of course, it is also necessary to know which stimuli and which processing channels are relevant to the piloting task. The question of which stimuli and which processing channels are relevant was addressed through the use of task analysis. The spectrum of the input signal was derived from task analysis of standard maneuvers (the pop-up ground attack was treated in detail). The spectra of disturbance motion cannot be derived from task analysis, of course, but the method can account for disturbance motion if it is included in the input spectrum. The transfer functions of pilot physiological systems were drawn from models described in the existing literature. The method is limited in that it does not address sensory and perceptual cross coupling or other intermodal effects.

Techniques of task analysis suitable for the CUMOD application have not previously been standardized. Although numerous approaches to task analysis are available (see, for example, Meister, (1985)), none was found suitable to provide the kind of information required for the type of analysis contemplated. A specialized task analysis technique was, therefore, developed specifically for the CUMOD study.

The task analysis method involves studying the kinematics and pilot control operations involved in performing actual flight maneuvers. Knowing the kinematics and control requirements, the forces and motion stimuli acting on the pilot may be identified and quantified. In the absence of empirical flight data on actual aircraft operations, the time histories of relevant

kinematic parameters can then be extracted from the analysis in a straightforward way. The Fourier transforms of these time histories characterize the input signal required by the frequency domain analysis.

In addition to quantitative information, the task analysis also provides a taxonomy of the cues and sensory effects a pilot experiences while performing the maneuver being studied. The analysis includes a study of these stimuli to determine whether any scientific evidence exists for their relevance to pilot performance. The terminology for describing and classifying stimuli is derived from a specific conceptual model of pilot control developed for the CUMOD study.

Task analysis fulfilled two main roles in the context of the CUMOD effort. The first was to provide the quantitative data about motion in flight from which to construct the spectra which are central to the analysis of simulator motion cuing. The second role was to provide a framework for classifying and studying individual cues and sensory effects as they relate to training and performance in flight. Analysis of the cues and other sensory effects involved in a given maneuver provides guidance as to what types of stimuli are relevant and thus guides the effort to translate the somewhat abstract information of a motion spectrum chart toward specific device technology.

The combination of task analysis and linear signal processing analysis effectively identifies the regions of the motion spectrum which are typically excited by flight, and presents the data in a way that the responses of simulation devices and of human perceptual systems may be directly compared to corresponding responses in the actual flight environment. In this way the technology development effort can be directed to concentrate on relevant stimuli: those which are both excited by flight dynamics and detected by the human subject--and not already treated by existing technology. In addition, it is also essential to study the question of which stimuli perceived by the human are actually used by the aircrew for control or are otherwise relevant to training. Although this last question is addressed to some extent by the task analysis technique developed for the CUMOD study, it is one best treated by experimental research using the new technology. The interpretation and decision-making processes are much too complex, too variable among individuals, and too poorly understood to permit very effective modeling at the level required for an accurate assessment of the usefulness of specific proposed cuing devices. This is not to say that intelligent conjectures are not useful in directing the research, or that no experimental research already exists based on advanced cuing devices, but only that no conclusive validation can be drawn from analysis alone.

History provides a useful cautionary example of both the advantages and the dangers of this type of approach to the development of technology for human-machine interaction. With the advances in audio recording technology in the 1920s and 1930s, high-fidelity audio recording became a possibility. In order to answer the question, "What is high-fidelity?", Harvey Fletcher of Bell Laboratories studied the response of the human ear and also the spectra of sound from various sources. The result was the famous Fletcher-Munson diagram, which demonstrates that in order to reproduce all the audible sounds an orchestra produces, a bandwidth of 20 Hz to 20 kHz and a dynamic range of about 120 dB are required. The theory worked very well: high fidelity recording is very convincing. But there were some surprises. One is that listeners could hear even the very lowest notes present in music even when played on equipment which could not reproduce tones of frequency less than a few hundred Hz. The reason for this is that the human auditory perceptual system is capable of inferring the presence of the fundamental and low-lying harmonics of a harmonic tone. The information to do this is present in the spacing of the higher Fourier components--even if the fundamental itself is not present. This effect only works on harmonic program material; but, of course, most music is composed of just that type of sound.

The second big surprise came from the opposite end of the spectrum. With the advent of high-speed digital recording, the question arose, "What is the optimum sampling frequency?" The Nyquist theorem and the Fletcher-Munson diagram give the answer very neatly: Fletcher says you must reproduce up to 20 kHz, and Nyquist says that the minimum sampling rate for complete reproduction is twice the highest frequency component of the source spectrum. Hence, 40 kHz sampling is all that is required. A 40 kHz sampling rate works tolerably well, but even unsophisticated listeners can detect improvements in fidelity up to 100 kHz sampling rates. Evidently, the ear, possibly through non-linear coupling, makes use of acoustic components far above the range of direct detection. Doubtless, similar opportunities and pitfalls await in the challenge of reproducing the sensations of flight.

1.4 A Guide to the Report

This report contains the results of the Phase I CUMOD study. Sections 2, 3, and 4 comprise the theoretical material developed to support the design of new-technology experimental cuing devices. The central result presented is a method of studying and characterizing aircraft motions, pilot responses to those motions, and the uses pilots make of their perceptions in the process of piloting. Section 2 presents a conceptual model of pilot control which provides a self-consistent framework for the discussion which follows. Section 3 then presents an analytical method of studying the relevance of cuing devices. The method

uses the tools of linear analysis to study the dynamic properties of force and motion cuing in terms of the relationship between the pilot sensation of motion cues involved in typical aircraft maneuvers and the pilot sensation of the corresponding synthetic cues produced by a simulator equipped with force and motion cuing devices. Section 3 also includes a description of a method of task analysis which provides both the quantitative data for the frequency domain analysis and a taxonomy of cues and other effects conveniently organized for study.

As a worked example of the methods described, the task analysis method is applied to the pop-up ground attack maneuver as used in the USAF F-4 training program. The results are treated using the spectral analysis technique and methods of cuing are discussed in the light of the results of the analysis.

Section 4 discusses several possibilities for motion cuing devices using new technologies.

Section 5 suggests several ways in which this theoretical work should be expanded. It also introduces a proposed experimental program.

Other specific, self-contained products may be found in the appendices. These include the bibliography which resulted from the literature search, and reports on the specific candidate cuing techniques found to be most promising for empirical investigation.

2.0 A Conceptual Model of Pilot Control

2.1 Introduction

The task analysis method used in the CUMOD study is based on a particular conceptual model of pilot control. The model described in this section provides specific definitions of terms, a framework of organization of the elements of analysis, and a motivation for choosing particular analytical techniques.

2.2 Discussion

Figure 2.2-1 shows a schematic representation of the information flow and information processing which takes place in the overall process of piloting an airplane. There are four types of symbols shown in the diagram. Round bubbles stand for bodies of information; the flags on the round bubbles show the organization of information in the bubbles; rectangular bubbles represent processes by which information is transformed or used to create new information; and the arrows or pipelines represent channels of information flow. A suggestive way in which to read the chart is to follow the pipelines saying that the contents of a round bubble act through the connected rectangular bubbles to create or alter the contents of the subsequent round bubble. For example, Pilot Actions act through Control Laws to create or alter the Status, which acts through the Pilot Environment Interaction to create Cues, etc. The diagram is very similar to classical data flow diagrams or control system diagrams, and, indeed, analogies to these types of charts are very helpful in understanding, interpreting and analyzing the concept the diagram represents.

The resemblance to a control system in which negative feedback is used to regulate a parameter affected by disturbance is not accidental. The task of a pilot is, at an elementary level, to control the state of the mechanical system so that it conforms to particular mission requirements despite disturbances outside the pilot's control. The Status bubble is a summing junction for disturbances; the Situation bubble includes a summing junction for the fixed mission requirements and the Control Laws bubble is a feedback loop which acts to stabilize the complete human-machine system.

Table 2.2-1 gives a summary of definitions of the terms used in this model. Although these terms are chosen to be as familiar and as common-sensical as possible, they do have specific meanings in the context of this model.

The Status bubble represents the physical, quantitative state of the aircraft and its associated systems. The Status is completely objective and, most probably, completely quantifiable. Note that the Status includes those aspects of the physical environment which are relevant to system functioning, and

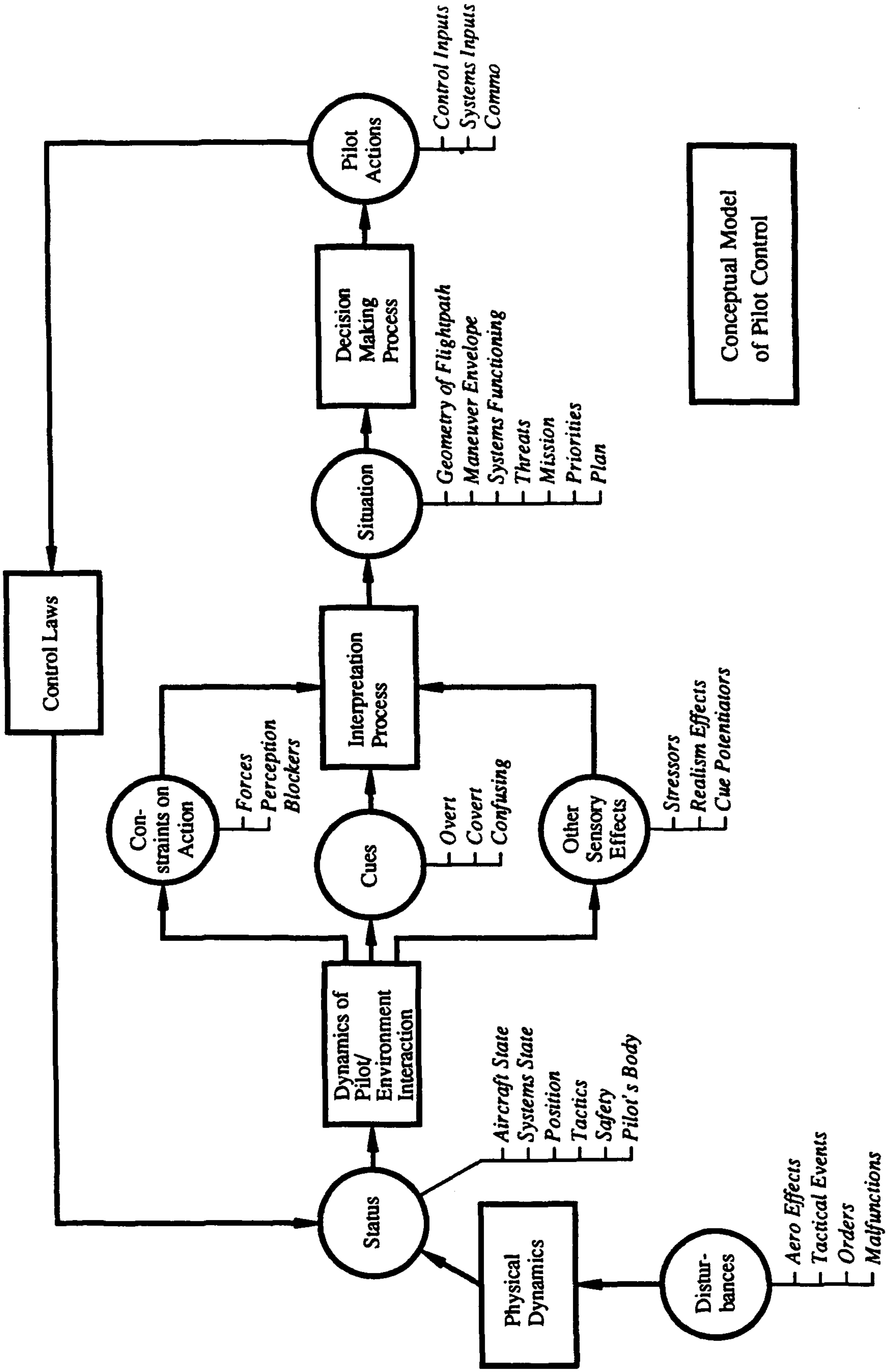

Figure 2.2-1 A Conceptual Model of Pilot Control.

includes the physiological state of the pilot's body. The key idea is that the status is objective and based in the physical. In a very real sense, the data pool of a flight simulator computer program is the simulator's representation of the status of the simulated aircraft and its environment. Although many simulators do not include pilot physiological state, some do--and any technology coming out of CUMOD most certainly will.

The Status can be affected by pilot actions (control inputs, for example) and by outside disturbances. The Disturbance bubble represents all effects which may cause the Status to change and which are outside the control of the pilot. A wind gust, for instance, will change the aircraft attitude. A tactical event such as the firing of an enemy weapon creates a change in the physical environment of the aircraft. Certainly a hit by an enemy weapon causes a state change in the aircraft and its systems! Disturbances such as tactical events and orders received by the aircrew are included in changes to the Status rather than somehow being folded into the mission (which is considered in the Situation bubble) because the aircrew comes to know of these disturbances through physical processes that are part of the system. Orders are received over the radio--a subsystem with physical properties and which presents itself to the pilot through his senses. Tactical events like weapons launches are evident to the pilot through optical processes and through the pilot's sense of sight.

Disturbances thus act through the physical dynamics of the complete system. The Physical Dynamics bubble represents the processes by which Disturbances create changes in the Status. For example, a wind gust acts through the aerodynamic properties of the airframe to create a change in attitude.

The Status is distinct from the Situation in that the Situation is the pilot's mental concept of the status and its relationship to the mission. The Situation will certainly contain many elements corresponding to elements of the Status but the Situation may or may not accurately reflect the Status. The Situation is not necessarily objective or quantitative: it includes feelings and hunches and assessments and concepts like what the objective of the mission is. The Situation is most distinct from the Status in that the Status is cast in terms suitable for description while the Situation is cast in terms suitable for decision making. The Situation includes the pilot's predictions about the future.

The process by which the pilot develops his Situation concept from the Status is the central question being addressed by CUMOD and by the task analysis this model of pilot control is designed to support. Simulators can be made to model Control Laws and Physical Dynamics very accurately and faithfully, but the process by which the Status is perceived by the pilot suffers from the

inherent limitations of simulator cuing devices. Even the most modern computer image generators and visual display systems do not create faithful representations of visual scenery; motion systems do not faithfully recreate the accelerations of an aircraft in combat. The Environment bubble contains all the physical, psychophysical and physiological processes by which the status manifests itself to the pilot's interpretative faculties. It contains all the processes by which the status produces stimuli, and by which the stimuli are sensed by the pilot. For example, a Status change such as a pitchup motion due to a wind gust will, by the laws of mechanics produce an upward acceleration of the pilot, which in turn requires a reaction force against the pilot's seat, which produces compression of the tissues of the pilot's buttocks, which causes nervous impulses to be sent to the pilot's brain, where certain neural processing takes place, which results in a sensation which the pilot can interpret as a perception of being pushed up. Of course, that perception of being "pushed up" is also due to information passed through other physical and sensory channels. The sensation of buttocks pressure is one of the several sensory effects that are the output of the Environment bubble as a result of the pitchup Status change.

The outputs of the very complex Environment bubble are stimuli. But, in truth, some stimuli are so heavily processed at an unconscious and reflexive level that, by the time they are sensed by the subject, they already have had some interpretation and are sensed directly at the level of perception--a perception being the result of sensations that have been interpreted to have some elementary kind of meaning. For the purposes of this model, it will suffice to admit as stimuli those perceptions which do not carry information which addresses itself directly to the Status. A primary example would be a visual image. Strictly speaking, the stimulus is a pattern of light falling on the retina and the associated sensation is some sort of pattern of neural activity in the optical cortex of the brain which is then experienced as a visual image. The perception would be, for example, a horizon. But for all practical purposes, the human visual system is constituted to automatically interpret a horizontal border as a horizon. An advanced simulator using the type of technology envisioned by CUMOD will take advantage of this level of automatic processing--and the many illusions which result--to create perceptions of force and motion relevant to high performance flight even though the simulator is not itself in motion.

A more detailed discussion of the classification of stimuli output from the Environment bubble may be found below. The essential point is that the Environment bubble includes a very complex array of types of information processing but results in the sensations and perceptions which the pilot interprets to form his Situation concept.

The pilot uses his Situation concept to make decisions about what actions to take. The Decision Making Process includes all this mental activity, some conscious, some unconscious, and some even reflexive. The pilot acts on his decisions by taking actions to change the Status. Pilot Actions include control inputs, aircraft systems inputs and communications. These actions all affect the Status in a lawful fashion through the Control Laws. For example, a motion of the stick acts through the mechanics of the control system to deflect a control surface. The deflection of the control surface causes, according to aerodynamic laws, forces to be exerted on the aircraft, which in turn responds according to the laws of mechanics to change its Status.

Now the control laws governing the response of the aircraft could be placed in the Control Laws bubble, or in the Environment Bubble, depending on the details of the definition of the Status. For instance, if deflection angle of the elevator is part of the Status, then the aerodynamic response due to elevator deflection could be considered to be part of the Environment. On the other hand, if pitch rate is part of the Status, then the aerodynamics of control response are part of the Control Laws. Either arrangement is self consistent, but for the purposes of this model it is more useful to keep only processes which bear on perception in Environment and relegate all others to Control Laws. This will not prevent including both control surface deflection and the kinematic state resulting from the deflection in the Status.

Table 2.2-1. DEFINITIONS OF TERMS USED IN THE MODEL OF PILOT CONTROL

STATUS

The physical state of the aircraft, pilot and associated systems, including their physical relationship to the environment.

DISTURBANCES

Disturbances are events or conditions which act through the dynamics of the physical environment and the aircraft to change the status.

CUES

Perceptions interpreted by the pilot to form a concept of the flight situation.

. OVERT CUES

Cues the pilot can consciously identify and interpret.

. . PRIMARY CUES

Cues used to motivate definite control or system inputs.

. . SECONDARY CUES

Cues used to support or enhance the information conveyed by primary cues.

. COVERT CUES

Cues the pilot cannot (or does not) consciously identify, but which contribute to the situation concept.

. CONFUSING CUES

Perceptions which have all the attributes of cues, but which carry incorrect or irrelevant information, and lead to an incorrect situation concept. Cues derived from illusions.

OTHER EFFECTS

Perceptions or sensory stimuli which do not function as cues but nevertheless are important for pilot acceptance of the simulation.

- STRESSORS

  Sensory effects which add to the pilot workload or stress load without conveying significant information on which to base pilot decisions, or without preventing pilot action.

- REALISM EFFECTS

  Sensory effects which convey information about the nature of the environment, but which do not convey specific information on which to base pilot decisions.

- CUE POTENTIATORS

  Sensory effects which are not cues in themselves, but which emphasize or draw attention to cues.

CONSTRAINTS ON ACTION

Physical or psychophysical effects which interfere with the perception or interpretation of cues, or make certain pilot actions physically difficult or impossible.

- FORCES

  Constraints on action which act by physically interfering with motion.

- PERCEPTION BLOCKERS

  Constraints on action which act by creating physiological or psychophysical conditions which interfere with perception.

SITUATION

The pilot's mental concept or understanding of the status and its relationship to the mission in terms suitable for decision making. The situation includes predictions about future status.

PILOT ACTIONS

Specific actions the pilot performs in order to influence the status. Pilot actions are the result of decisions motivated by analysis of the situation.

PHYSICAL DYNAMICS

The physical laws controlling the behavior of the aircraft, its systems, the physical environment and all its elements.

CONTROL LAWS

The laws governing the reaction of the aircraft and its systems to pilot actions.

DYNAMICS OF PILOT/ENVIRONMENT INTERACTION

The laws governing the processes by which the pilot is physically affected by the status. These processes include the various mechanisms of physical interaction between the pilot and his environment, and the physiological, anatomical, and psychophysical processes invoked by physical stimulation of the pilot.

INTERPRETATION PROCESS

The mental and psychophysical processes by which the pilot uses information about his environment to formulate a concept of the situation.

DECISION MAKING PROCESS

The mental processes by which the pilot analyzes the situation and formulates appropriate pilot actions. These processes occur at all levels, from reflexes, through habits of training, to intellectual analysis.

2.3 Classification of Pilot Stimuli

2.3.1 Cues

A cue is a perception which is interpreted by the pilot in order for him to form a concept of the flight situation. Based on the situation, the pilot will make decisions about what actions to take. Cues are usually directly related to a specific element of the aircraft status and are interpreted to provide information about a corresponding element of the situation. In a steep power turn, for example, the pilot controls bank angle by visual reference to the geometrical relationship of the horizon to the cowling and cockpit structures. If the pilot wants a 40 degree bank but the aircraft is actually in a 30 degree bank, the horizon cue will be that the horizon is tilted 30 degrees with respect to some reference structure on the aircraft. The pilot will interpret this cue to mean that the situation is "not enough bank," and will decide to take the action to add more bank. An accomplished pilot will do all this more or less automatically, but a student may well actually articulate this sequence of events to himself.

2.3.2 Overt Cues

Overt cues are cues which the pilot can directly identify and consciously or verbally interpret. These are the cues which an instructor articulates to the student and teaches him to use consciously. In a steep power turn, for example, the pilot controls pitch by reference to the relationship of the visual horizon to a selected point in the windshield. The pilot knows he uses this cue and the instructor can explain the cue and its interpretation to the student.

2.3.3 Primary Cues

Overt cues may be further broken down into primary and secondary cues. A primary cue is a cue the pilot uses as an immediate basis for positive control inputs. The horizon position in the case of the steep turn is a good example of a primary pitch cue.

2.3.4 Secondary Cues

The pilot needs to know, however, where in the windshield to place the horizon. Partly he picks his point from memory built up from experience, and partly he selects the point based on the initial position of the horizon in the windshield, but he also cross-checks the altimeter and Vertical Speed Indicator (VSI) to verify and modify the placement he has chosen. He does not base his stick inputs directly on the altimeter reading; he bases his stick inputs on the primary cue of horizon position. The altimeter reading is thus a secondary overt pitch cue for a steep turn.

2.3.5 Covert Cues

In addition to the information gained from overt cues, a pilot forms much of his concept of the flight situation from covert cues--perceptions of which he is not fully aware, or at least cannot describe. Reflex forms the basis for many of these cues. For example, in the steep turn case, the pilot may make a control input error, or the aircraft might be buffeted by turbulence inducing a roll disturbance. Although the disturbance will be evidenced in the overt cue offered by the visual horizon, the pilot will also perceive the roll motion through his vestibular system, through his peripheral vision, and through various "seat of the pants" reaction forces. Very likely, he will respond almost reflexively to these cues and make a correcting stick input almost before he is consciously aware of the change in the flight situation. A typical reaction will be to put in an initial correction in response to the covert cue and stop the correction based on the primary overt cue. This is the reason that it is easier to fly normal maneuvers in a simulator with a motion system than in one without.

2.3.6 Confusing Cues

In addition to the perceptions the pilot uses to form his situation concept, he is also subject to perceptions which appear to be valid cues, but in fact convey information which is incorrect, confusing, misleading, or just irrelevant. These are confusing cues. Again using the steep turn example, the pilot watches the visual horizon for both pitch and bank cues. A sloping cloud deck, however, may give the false impression of excessive bank and a nose low pitch attitude. The pilot faces the task of separating the confusing attitude cues offered by the sloping cloud deck from the appropriate cues offered by the true horizon. The pilot performs these discriminations from a combination of wariness born of experience, attention to the details of the presenting phenomena, and the judicious use of secondary cues.

Confusing cues, particularly if they are covert, can be particularly insidious in their effects on the pilot's situation concept. The effect of ground rush in a low altitude downwind turn is a classic example. Except in a few special circumstances, the kinematics and aerodynamics of a downwind turn are the same as those of any other turn, but the unexpected increase in groundspeed--which is very visible at low altitudes--leads the turning pilot to overbank and pull the nose up. These inappropriate pilot actions, based on an incorrect situation concept, can sometimes result in a low altitude accelerated maneuver stall with disastrous outcome.

The human perceptual system is not well evolved for functioning in a flight environment. Consequently, a pilot's nervous system

tends to assess cues under the assumption that the pilot is standing on the ground rather than flying through the air. Illusion is thus the aviator's constant companion, and a major impediment to both safety and mission fulfillment. Indeed, a large component of "flight experience"--that commodity so assiduously pursued by aviators--is simply exposure to the many illusions of flight, both subtle and dramatic. One of the student pilot's training objectives is to learn to distinguish and ignore the confusing cues which are the basis of so much illusion.

2.3.7 Other Effects

Cues are perceptions and, of course, begin as sensory effects. But there are numerous sensory effects which have little or no function as cues; that is, they do not convey information about the aircraft state which is relevant for making control or supervisory decisions. Nevertheless, these effects do have significant influence on pilot behavior and performance. These non-cue sensory effects include stressors, which increase the amount of effort a pilot must expend in order to perform effectively; realism effects, which improve the acceptability of the simulation; and cue potentiators, those sensations and perceptions which aren't quite strong enough or distinct enough to be classified as cues, but which emphasize cues or direct a pilot's attention to them. Sensory effects are important because their absence is noticed by pilots when they are not present--even if they are not truly necessary for control.

Stressors are sensations due to factors such as heat, vibration, noise, or glare. They increase the amount of effort the pilot must exert in order to perform at an acceptable level, and they may induce coping strategies, but they are not informative in themselves. Consequently, stressors are important to the environment, but are not cues.

Similarly, realism effects, such as the realistic appearance of terrain or weather phenomena, do not carry essential information about the state, but may nevertheless influence the pilot's formation of a situation concept simply by giving a greater sense of immediacy to the environment. Realism effects are often cited as important to pilot acceptance of the simulation.

Cue potentiators are sensory effects which very nearly belong among the cues themselves, but are not effects which carry the actual control information the pilot uses to form his situation concept. The importance of cue potentiators lies in directing the pilot's attention to the cuing effect itself. For example, g-loading is a direct consequence of turning at a specific angle of bank. The pilot does not regulate bank angle by sensing his g-load, however. Rather, he regulates bank angle visually by reference to the visual horizon, his altitude gyro, or his turn

rate gyro. Sustained g in the turn helps the pilot to focus on the task of regulating bank, and a change in g-load in a turn will alert the pilot to check his bank angle.

Seat-of-the-pants sensations are notoriously inaccurate as cues for aircraft control. They are important, however, in directing the pilot's attention to the reliable indicators of aircraft state. The instructor-pilot constantly admonishes his student to be sensitive to the seat of his pants, but not to fly by it. Similarly, pilots use engine and slipstream sounds to potentiate visual pitch control cues.

2.3.8 Constraints on Action

Very similar to stressors, are more gross bodily effects which physically constrain, or actually inhibit, certain pilot actions, narrowing the scope of alternative actions the pilot has at his disposal. The most obvious of these is extreme G-loading. Accelerated maneuvers develop large reaction forces which decrease the accuracy with which a pilot can move and position his limbs, and which limit the amount of head motion he can perform. The cardiovascular effects of acceleration can result in G-dimming, blackout, and even loss of consciousness. Constraints on action may be grouped into two large categories: forces and perception blockers. Forces constrain action by physically preventing the pilot from performing certain acts. They are usually the result of G-loading and result in restricted ranges of motion, reduced speed of motion, reduced accuracy of positioning, increased muscular effort resulting in fatigue, and increased mental effort required to compensate and to take defensive action (such as straining). Perception blockers constrain pilot action by making information unavailable for decision making. Blackout due to acceleration forces obviously results in the loss of all visual cues. Increased noise due to weapons effects may mask useful auditory cues such as engine sounds and radio communications. Airframe vibration or G-loading may mask force-feedback cues from the control stick or blur the pilot's vision. All constraints on action act through physiological and anatomical mechanisms, but they result in interference with the perception and interpretation of cues.

The distinction between stressors and constraints on action is often a matter of degree. For example, vibration and acoustic noise is annoying and fatigue inducing. At low levels they certainly affect pilot behavior and performance, but do not physically prevent any pilot action or perception of cues. At higher levels, however, acoustic noise may block perception of important acoustic cues, or may require protective measures which themselves block auditory cues or limit freedom of motion. Similarly, high levels of vibration may reduce touch sensitivity or the accuracy of fine motor control so as to prevent the pilot from performing certain tasks.

3.0 A Method for Need-Based Analysis of Cuing Devices

3.1 Human Perception of Motion

3.1.1 Discussion

Humans do not directly perceive the nature of their surroundings or their motion through it. A person's concept of his surroundings and of his own motion is built up by the central nervous system at various levels of consciousness by integrating the nervous signals from a wide variety of sensory organs. Although the eye, for example, is physically much like a photographic camera, it does not, in any real sense, send pictures to the brain. Rather, the brain uses the signals on the optic nerves to infer a concept of the physical space around the subject. Humans experience this concept as a visual image--but an image quite different in character from those captured by the retinas. Even persons with some types of gross optical defects can learn to form a complete, continuous visual image; but persons with no visual experience of certain surroundings find it impossible to organize the visual sensations into a meaningful perception of the space.

Although intimately connected, the processes of sensation and perception are conceptually quite distinct. Sensation is the physical process by which a sensory organ responds to a stimulus and sends a signal to the central nervous system. Perception is the integrative process by which the nervous system builds up a mental concept of body state and surroundings; it is the process by which we give meaning to sensation. Sensation is the physical exchange of energy with the environment and the subsequent physical transposition of nervous signals; perception is the mental process of interpretation of sensations.

Physically, the response of a sensory organ to stimulation is to change its rate of neural discharge. Consequently the afferent firing rate may be considered a signal indicating the strength and, in some cases, the sign of particular stimulus. The quality of stimulation--flavor, odor, color, coldness, hardness--is an interpretation made by the cognitive and subcognitive processes of the perceptual system, and is often based on combinations of signals received from different sensory end organs and depends upon physical signal processing throughout the nervous system. Each sensory organ itself can properly be considered a transducer subject to the same kinds of analytical treatment used on artificial transducers.

Perception is vastly more complex than sensation, and not well understood in any detail. Nevertheless, it is clear that the perceptual system is remarkably flexible: it can develop the same accurate percept based on different sets of sensations--even if the sensory data is not entirely self-consistent. Similarly,

the brain can construct an illusory percept from sensory data which, whether by accident or design, is consistent with that percept--even if incomplete. Visual illusions of fictitious spaces, or simple illusions of self motion, are particularly easy to create through pictures, cinema, video--and simulator visual systems. Faithful replication of all the sensations due to aircraft motion is not possible in a simulator, but because of the inherent flexibility of the perceptual process, useable replication of the perception of aircraft motion is possible if enough artificially produced sensory data are provided to the brain.

The most direct perceptions of self-motion derive from sensations received by the visual and vestibular systems. Although the visual system sometimes dominates the vestibular system in pure motion perception, the two types of sensory data are largely complementary. Vision is highly developed for detecting relative position, attitude, and changes thereof; the non-auditory labyrinth is highly developed for detecting angular and linear acceleration and angular velocity, (before adaptation), particularly at high frequencies. Each complements the other. For example, vision improves the accuracy of integration of velocity and acceleration signals received by the semicircular canals and otoliths, while the labyrinth provides the signals necessary for inertial stabilization of the eyes during head movement.

Humans also infer motion from somatosensory stimuli. A particularly dramatic example is the limb and head loading a pilot feels during acceleration. Numerous other sensations also contribute to the sensation of motion: acceleration forces produce pressure on supported body parts; clothing and equipment change weight and shift on the body; the buttocks, back, and elbows scrub against the seat; internal organs are compressed and shifted resulting in an impressive variety of physiological consequences. The pilot's attempts at purposeful motion are affected both subtly and grossly by the acceleration force field.

All these effects are synergistic. Interestingly, aviation is sufficiently alien to humans that many combinations of the sensations associated with flying seem contradictory to the pilot, thus leading to illusions, vertigo, disorientation, and air sickness. Simulator cuing devices may take advantage of all these channels of stimulation to help build in the pilot an integrated perception of motion similar to that experienced in the real world despite the fundamental limitation that no sustained acceleration is possible. An optimum design, however, probably requires that the perceptions occurring in actual flight be well matched to the perceptions produced by the simulation equipment. Although subjective matching of synthetic and real-world perceptions may be important to the acceptability of a simulator, the critical test of success is that the synthetic and

real-world stimuli elicit similar pilot behaviors.

3.1.2 Sensory Models

The perception of motion by the human organism is a complex process which involves the processing of signals from several sensors into a percept of motion. It is well known that the sensory apparatus involved are the vestibular system, the haptic system, the visual system and, to a lesser extent, the auditory system. A description of these sensors is given in Borah et al. (1977). Since the perceptual process is an integrative process as illustrated in Figure 3.1.2-1, the mathematical models of this process should include not only models of the sensors but also the neural processing associated with the output of each transducer and the integration of these sensory afferents.

Models of the integration process are still a research issue and, consequently, were not included in this analysis. Discussions of the integration process can be found in Borah et al. (1977) and Zacharias (1977). The models utilized in the cuing analysis were essentially end organ models with some afferent processing where it is known. Models are included for the vestibular and haptic systems.

3.1.2.1 Vestibular System

Since the vestibular system comprises the semi-circular canals and the otoliths, models will be presented for both.

3.1.2.1.1 Semicircular Canals

The model of the semicircular canals is based on representing the canal dynamics as an overdamped second order system as proposed by Steinhausen in 1933. Coefficients for Steinhausen's model were first estimated by van Egmond, et al. in 1949, then subsequently refined by a number of researchers. In addition, adaptation terms proposed by Young & Oman in 1969 and Malcolm & Melvill-Jones in 1970 are included. The effect of rate sensitivity of one of the two types of hair cells is represented as a first order lead as proposed by Goldberg and Fernandez in 1971. Finally, neural processing delay of the semicircular canal afferent response may be included as a pure delay. Hence, the semicircular canal model used in our analysis was as follows; relating afferent firing rate (AFR) to angular acceleration α of the head:

$$\frac{AFR}{\alpha} = \left[\frac{K}{(\tau_L s+1)(\tau_s s+1)}\right]\left[\frac{\tau_a s}{\tau_a s+1}\right](\tau_v s+1)\, e^{-\tau_N s} \qquad (3.1.2\text{-}1)$$

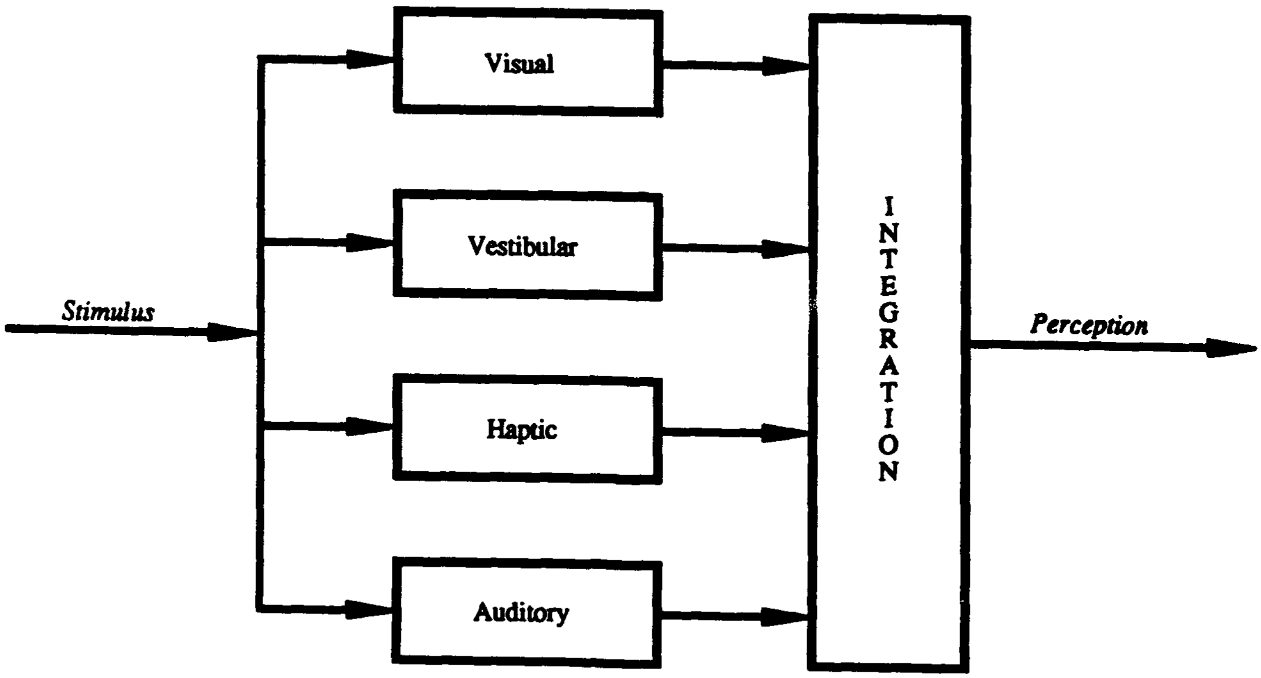

Figure 3.1.2-1 Diagram of the perceptual process

The first term in brackets is a model of the canal dynamics. The second term is a representation of the adaptation of the semicircular canals. The rate sensitivity is modeled by the third term and neural processing delay by the exponential term.

Values for the constants in equation 3.1.2.1 are given below.

$K = 1.0$	$\tau_a = 80$ sec
$\tau_L = 5.73$ sec	$\tau_v = 0.049$ sec
$\tau_s = 0.005$ sec	$\tau_n = 0.3$ sec

If τ_n is taken to be zero, then this formulation will reflect the work of Hosman and van der Vaart (1978, 1980). The value of 0.3 seconds is frequently used in manual control pilot models. There is also some controversy as to the value of τ_L: Borah et al. (1977) use 10 seconds as compared to the 5.73 sec recommended by Goldberg and Fernandez (1971) and verified by Hosman and van der Vaart (1980). However, Ormsby and Young (1976) use 18 seconds, Young and Oman (1969) use 30 seconds for τ_a and 0.01 seconds for τ_v. A nonlinear term could also be included to account for threshold characteristics as was proposed by Borah et al. (1977).

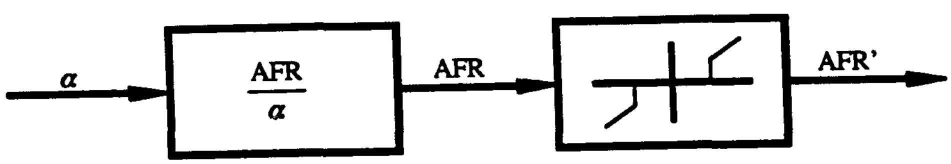

Figure 3.1.2-2 Semicircular canal threshold

In equation 3.1.2-1 AFR is the suprathreshold AFR. The issue of modeling the threshold is complicated and if the latest research were employed, it would be modeled based on signal detection theory. For the initial work of this study, the threshold was not considered. A possible simplification would be a pure threshold on the input acceleration (See Figure 3.1.2-2). Also in this study, all three canals were modeled as above. In future work, the canal differences suggested by Guedry (1989) can be included.

3.1.2.1.2 Otoliths

The formulation of the otolith models is not as straightforward as the semicircular canals in that there is not as wide acceptance of the form. The model proposed by Fernandez and Goldberg (1976) which was validated using squirrel monkeys, is used in our analysis:

$$\frac{AFR}{SF} = \left[\frac{K_o}{1+\tau_o s}\right]\left[\frac{1+K_a\tau_a s}{1+\tau_a s}\right]\left[1+K_v(\tau_v s)^{K_v}\right] \qquad (3.1.2\text{-}2)$$

Fernandez and Goldberg (1976) suggest the following values for the constants in equation (3.1.2-2). SF is specific force.

$K_o = 25.6$	$K_v = 0.188$ sec
$K_a = 1.12$	$\tau_v = 40.0$ sec
$\tau_a = 69$ sec	$\tau_o = 0.016$ sec

The threshold may be modeled as suggested for the semicircular canals or as a non-linearity as proposed by Borah et al. (1977). Their model is included as figure 3.1.2-3 showing the non-linearity and also indicating a separate saccule non-linearity. There are also some other differences between the formulations of equation 3.1.2-2 and Figure 3.1.2-3 as well. While the latter might better account for non-linearities, the formulation of equation 3.1.2-2 was used in this study, because of its better representation of the linear response of the otoliths.

3.1.2.2 Haptic System

The models of the haptic system employed in this study are taken from Borah et al. (1977). First a tactile model of the buttocks encompassing the Pacinian Corpuscles and type I and II cutaneous sensors was suggested. This model, illustrated in Figure 3.1.2-4, employs body/seat compression dynamics as seen in the first block.

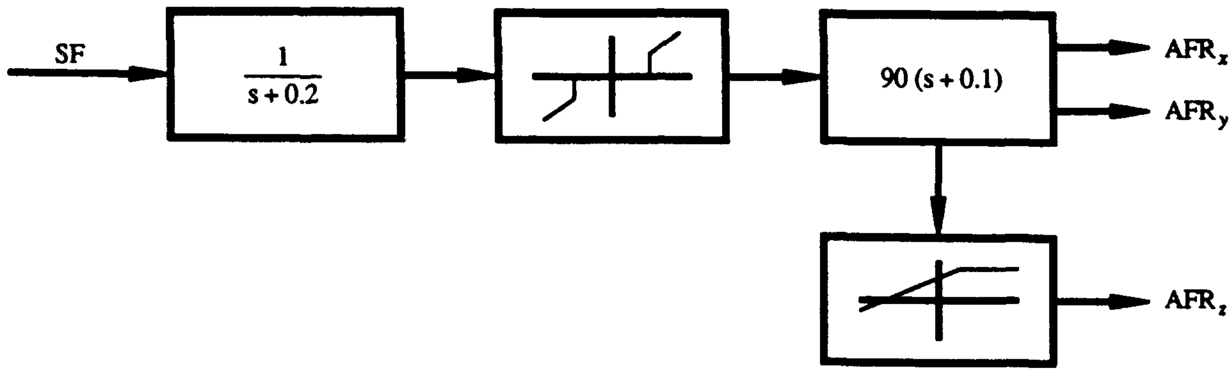

Figure 3.1.2-3 Otolith model including non-linearities

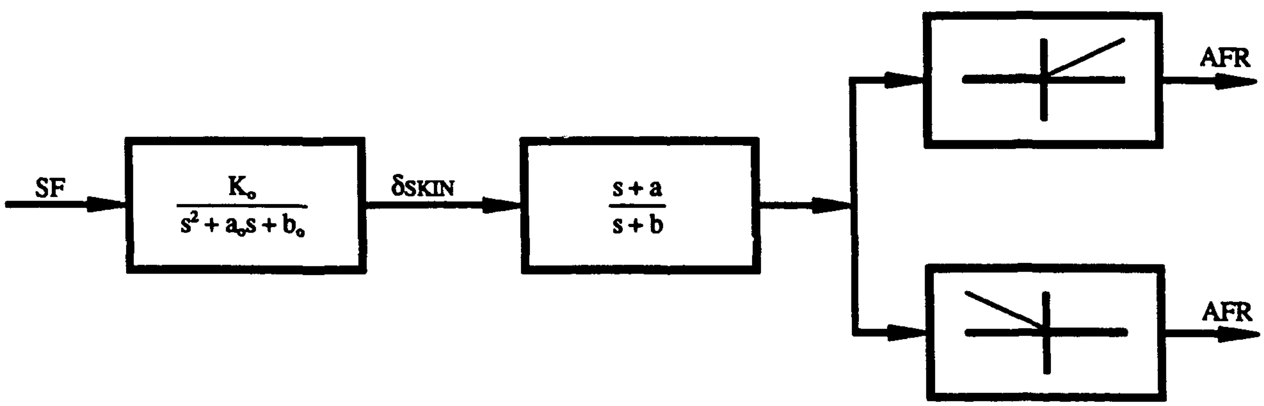

Figure 3.1.2-4 Tactile model of the buttocks

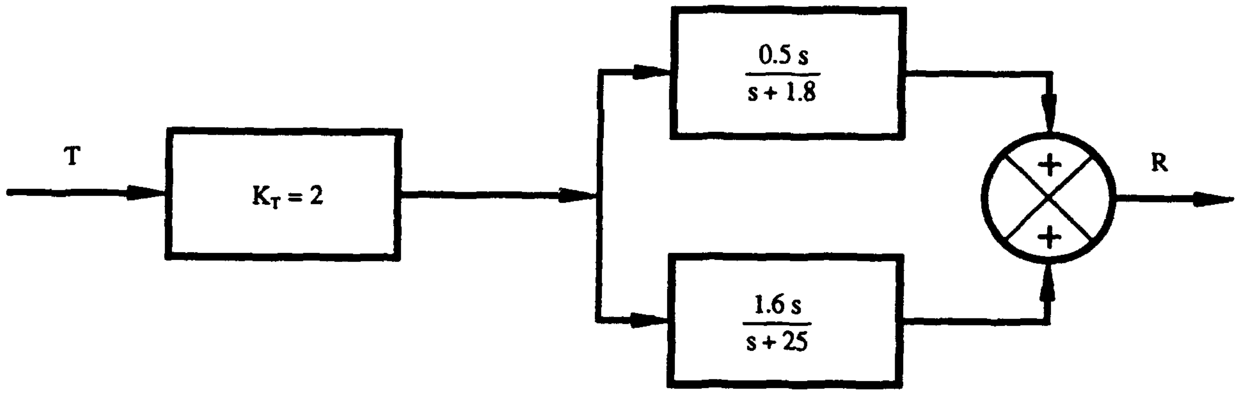

Figure 3.1.2-5 Golgi tendon model

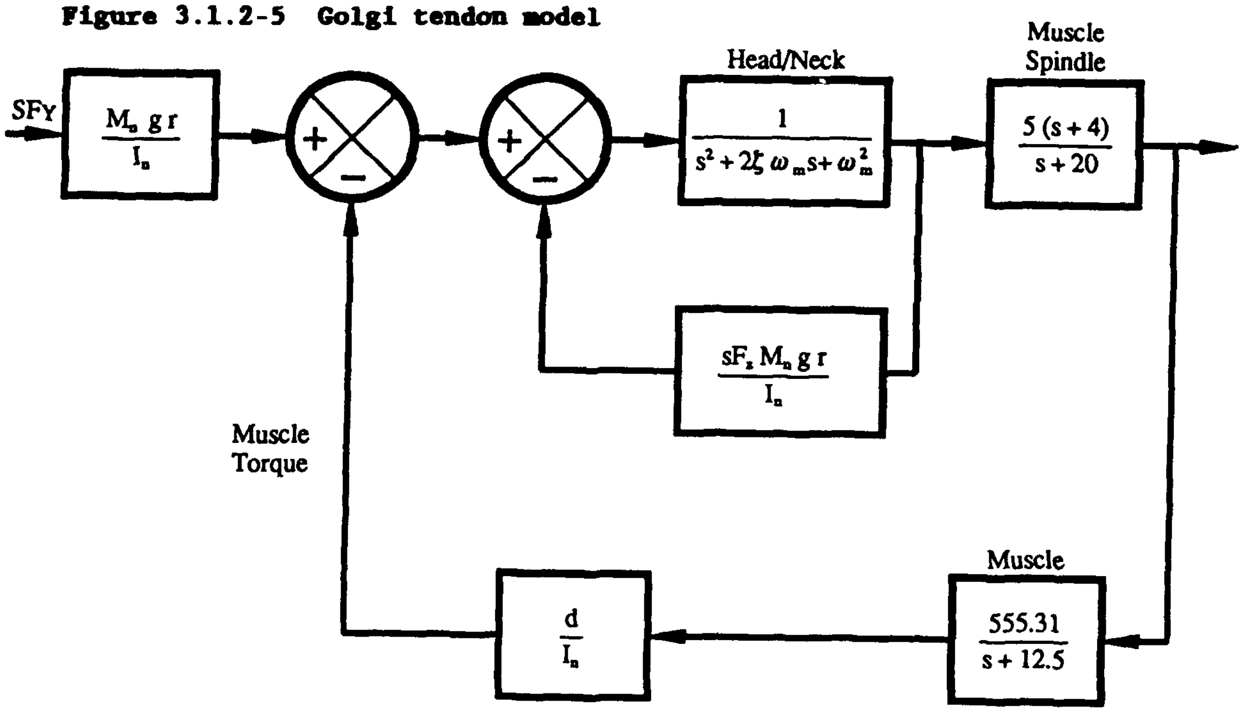

Figure 3.1.2-6 Head/Neck model

This second order representation was first postulated by Gum (1973). The second block presents the receptor dynamics represented by a first order lead/lag. The two parallel blocks contain a high pass representation of the Pacinian corpuscles at the top and the low pass characteristics of the type I and II cutaneous sensors in the lower block.

For a 70 kg man, the coefficients of the second order transfer function are $K_0 = 9.8$, $a_0 = 0.56$ and $b_0 = 453$. For the lead/lag term a = 0.01 rad/sec and b = 0.1 rad/sec.

The Golgi tendon model is given in Figure 3.1.2-5. The Golgi tendon organs transduce muscle tension. The model was derived from experimental data of Houk and Henneman (1967) and modified by Oman (see Borah et al. 1977). In this model, T is the tendon force and R is the AFR response.

A head/neck model is also presented. This model can be used for both head/neck loading and posturography analyses. The model is constructed as an inverted pendulum with muscular control torques. Gum (1973) first postulated this model and it was subsequently modified by Borah et al. (1977). Muscle dynamics and spindle feedback transfer functions were based largely on neurophysiological data. The head natural frequency and damping ratio were determined experimentally from a single subject and moment of inertia was approximated by Gum. Neck joint receptors were not included in this model. Further, it should be stated that this model was derived for motion in the lateral direction. The effect due to vestibular detection of motion is not included in this model.

$d = 0.075$ m	$m\omega_m = 7.81$ rad/sec
$I_n = 0.0304\ \mathrm{kg \cdot m^2}$	$r = 0.0498$ m
$M_n = 4.6$ kg	$\zeta = 1.0$

3.2 The Characteristics of Aircraft Motion

Aircraft--particularly modern, high performance combat aircraft--are capable of motions which are never used in actual flight. Some regions of the envelope are simply declared too dangerous and are, therefore, prohibited to the pilot; others are not tactically or operationally useful. Simulators, therefore, need not be designed to provide cues associated with all the possible motions of the aircraft--only with those motions which are actually undergone, which can be perceived by the human organism, and which are relevant to performance or training. A convenient way to represent aircraft motion for purpose of deriving its relevant characteristics is to express the range of actually occurring motions in the frequency domain. The spectrum associated with any specific motion parameter, such as roll angle

or vertical acceleration, can be computed by taking the Fourier transform of a sufficiently long sample of the time history of that parameter. The appropriate spectrum cannot be properly derived from the design parameters of the aircraft: it is not the aircraft's capabilities but rather its actual operational uses which matter. The ideal source of the appropriate motion time histories would be measurement of the motions of specific aircraft taken while the aircraft are flown in the roles for which the simulator is intended to provide training. Lacking actual aircraft operational data, however, some instructive observations may be made which are sufficient to demonstrate the approach. A detailed theoretical treatment of the pop-up ground attack maneuver is provided in Section 3.5.3 below.

Even in combat, pilots tend to fly specific, fairly well-defined maneuvers--level turn, climbing turn, split-S, etc. Each engagement is a particular sequence of these standard maneuvers, selected by the pilot as the developing tactical situation warrants. There are many exceptions, variations, and adjustments, of course, but generally a pilot can describe an engagement or a mission in terms of named maneuvers. Furthermore, each maneuver tends to be constructed of brief periods of acceleration onset, steady acceleration, and acceleration offset. This type of acceleration profile gives the pilot periods of relatively steady conditions which minimize his physical stress and which give him opportunities to assess the tactical situation. Figure 3.2-1 shows a graph of the vertical acceleration (G_z) during a hypothetical maneuver of this sort. The pilot generally maneuvers at $+G_z$ in order to bring about a change in state of the aircraft, and then he "unloads." If the "pull" is smoothly executed, then the curved portions of the profile have a characteristic serpentine shape which may be approximated as segments of sinusoids. Although we have made no empirical studies of actual aircraft flight data, the detailed theoretical study of the pop-up ground attack mission of the F-4 presented in section 3 supports this assertion.

The Fourier transform of a time-dependent function composed of sinusoidal-edged pulses is a complicated sum of sinusoids under an envelope with a characteristic $1/\omega + \omega/(\omega_0^2-\omega^2)$ dependence. The result is a function with a $1/\omega^3$ cutoff at the maximum frequency of the edge-forming sinusoids. Although the envelope is singular at zero frequency, the spectrum itself is not. The zero-frequency is just the total g-exposure--the time integral of the acceleration curve. Since the analysis is not concerned with the absolute amplitude of the spectrum, but rather with the relative contributions of different frequency regimes, it is necessary to normalize the spectrum by dividing the Fourier transform by the duration of the time history sample. This step conveniently renders the spectrum as a dimensionless function.

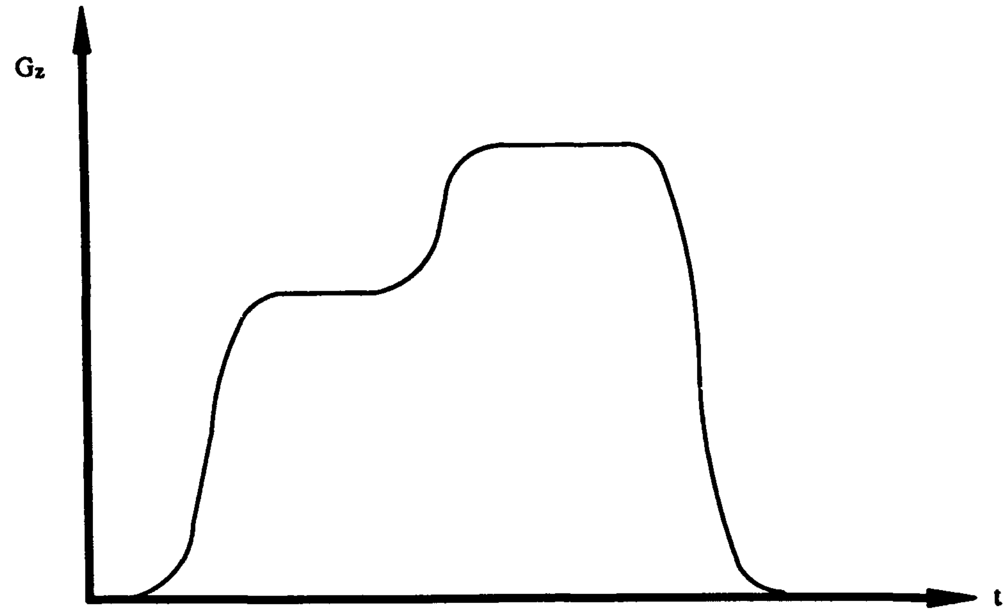

Figure 3.2-1. A segment of the time history of an idealized combat maneuver.

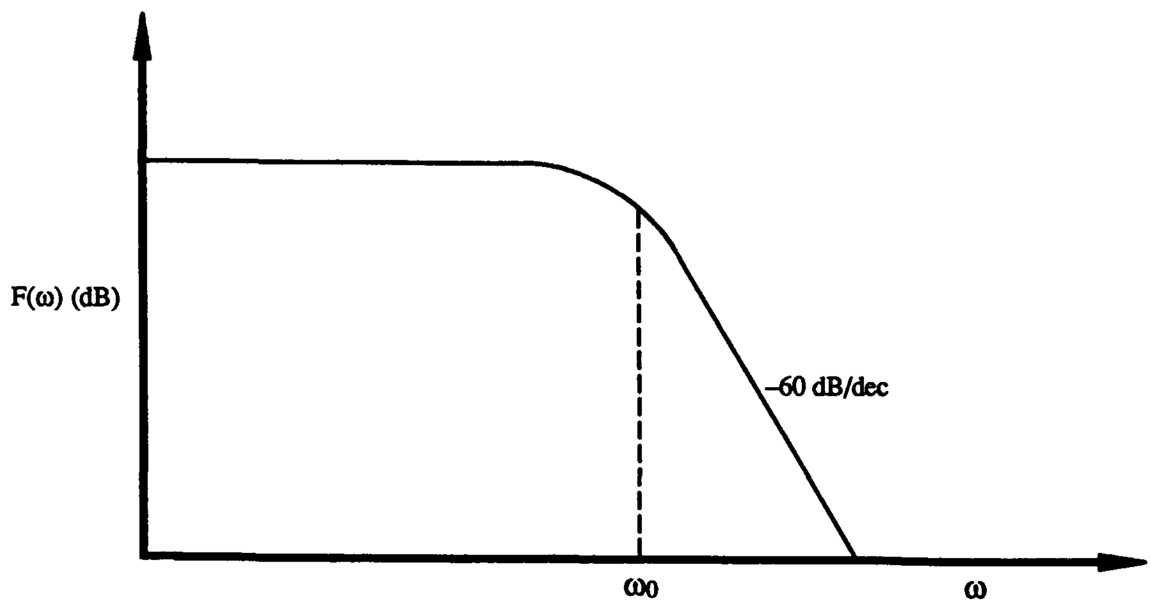

Figure 3.2-2. The form of the frequency domain representation of the vertical acceleration due to a long, idealized combat mission.

Since there is no reason to expect any coherence among the sinusoidal components of the spectrum, the details of the complex structure of the function are not significant in characterizing the motions involved in the mission under analysis. The important issue is the gross structure of the curve, or the envelope under which the fine structure lies. Unless the spectrum was derived from a very brief time history sample, its gross structure should be quite simple.

It is evident from these observations that, when expressed in decibels and plotted against the logarithm of frequency, the typical G_z spectrum representing any specific operational role will usually be fairly flat out to a distinct cutoff and then decline at -60 dB per decade. As a practical matter, it is often reasonable to characterize the aircraft motion entirely by its cutoff frequency since all frequencies less than the cutoff are significant to the simulation, and components above the cutoff diminish very rapidly with increasing frequency. It is convenient to define 0 dB as the maximum amplitude of the Fourier transform. In the case of vertical acceleration, the maximum will generally occur at zero frequency since pilots tend to avoid negative G. Thus for G_z, the procedure makes 0 dB correspond to the average acceleration over the duration of the mission. For a bipolar parameter such as roll rate, zero dB can be defined with reference to the RMS value of the parameter in question.

As a hypothetical illustrative example, consider a mission which involves pulls to 6G in 1 second. This pull constitutes a change of 5G in 1 second. Approximating the onset as a half cycle of a sinusoid, the characteristic frequency of the fastest pulls is therefore 0.5 Hz or 3.1 rad/sec. Consequently, the cutoff frequency acceleration spectrum is also 3.1 rad/sec. The Fourier transform of the sum of many such missions, normalized for mission length, is shown in Figure 3.2-2. The mixture of many pulses of G_z washes out all the fine structure, leaving only the characteristic 0.5 Hz cutoff. This function, $F(\omega)$, is a representation of the aircraft G_z in the frequency domain.

Similar analysis holds for other parameters describing aircraft motion. For the purpose of simulator force and motion cuing analysis, however, only four parameters need to be considered--provided that only coordinated flight is considered. These are vertical acceleration (G_z), pitch rate (q), longitudinal acceleration or thrust (G_x), and roll rate (p). Any other parameter may be derived from these, while this set provides the most direct coupling to human motion sensing channels.

3.2.1 Data Requirements for Aircraft Motion

Analysis of the kinematics of specific maneuvers is useful in determining the nature of the pilot's dynamic force and motion environment, but direct measurement of the appropriate parameters

in actual flight will provide a more accurate basis for spectral analysis. Different aircraft, different missions, and different geographical deployment locations will all present somewhat different characteristic motion spectra. Disturbance motion, in particular, is difficult to account for realistically on a theoretical basis. Simply measuring the dynamic characteristics of each aircraft-mission combination cuts through all questions and uncertainties regarding the actual mix of basic maneuvers, the effects of atmospheric phenomena, and the dynamic characteristics of individual aircraft types.

The relevant dynamical parameters are all detectable by accelerometers, so instrumentation of aircraft would be relatively simple, unobtrusive, and inexpensive. The two linear accelerations, G_z and G_x, are easily sensed directly with linear accelerometers. The two rotational rates, p and q, are most easily detected by integrating the outputs of rotational accelerometers placed on the appropriate axes. Since the time periods over which rotational rates are sustained is on the order of seconds, integration errors can be expected to be negligible. The ideal approach would be to instrument several aircraft in an operational squadron and gather data due to routine squadron operations. Enough data must be collected so that the addition of new data does not significantly affect the shapes of the resulting spectra.

If it turns out to be impractical to instrument operational squadron aircraft, then training aircraft would be suitable, although the question of the relationship between training activity and operational activity would require attention.

3.3 Analysis of Sensory Processing

If a sensory organ is viewed as a transducer which converts sensory stimuli into a neural signal, then the entire process of sensation, including the mechanisms of stimulus, may be analyzed using the classical tools of signal processing. In a linear system, the only requirements for faithful transmission of a signal are that the transmission channel have constant gain and a phase shift proportional to frequency. If these requirements are not met, the characteristics of the channel bandpass will be conferred on the signal.

Figure 3.3-1 shows a simplified block diagram of the sensory signal path from aircraft to afferent nerve fibers for both the real world and simulated cases. The only significant difference between the two cases is that, in the simulated world, the aircraft motion signals must pass through a motion cuing device, whereas in the real world it is the aircraft itself which transforms the aircraft motion to physical stimuli. For the sake of simplicity, we will take the aircraft to be a unity-gain channel, although, in fact, minor channel shaping is induced by

the dynamics of the aircraft seat and other factors. The frequency domain representation of the aircraft motion, whether simulated or real, is $F(\omega)$.

Each sense organ has its own response, characterized by a transfer function $T(\omega)$, based on a physical model. Models are available for all the principal organs of force and motion perception (cf. Borah, Young and Curry, (1977); Goldberg and Fernandez, (1976); Gum, (1973); Ormsby and Young, (1976)). Although the sense organs are not always linear in their responses, linear approximations make a good starting place for this type of analysis. As examples, the magnitude frequency response of the otoliths, based on a model due to Goldberg and Fernandez (1976), and a magnitude frequency response for the Pacinian corpuscles, based on a model due to Borah et al. (1977), are shown in Figure 3.3-2. The otoliths sense linear acceleration; the Pacinian corpuscles sense deep tissue pressure such as that exerted on the buttocks of a seated person. The plots are normalized so that zero dB is the gain at maximum sensitivity. In both cases, the input is the specific force stimulus and the output is afferent firing rate (AFR). The frequency-domain representation of the AFR in the real world case is called $A(\omega)$; in the simulated case it is called $S(\omega)$.

The AFR for each sensor in each case--real or simulated--is simply given by

$$A(\omega) = T(\omega)\ F(\omega)$$

$$S(\omega) = M(\omega)\ T(\omega)\ F(\omega)\ ,$$

where $M(\omega)$ is the transfer function of the cuing device stimulating a particular type of sense organ.

In terms of sensation in a specific channel, the fidelity of the simulation is characterized by the extent to which $A(\omega)$ and $S(\omega)$ are similar. In terms of perception, however, the fidelity of the simulation is determined by the details of the sensory integration processes. The perceptual system can use the sensor information available from all channels to infer a percept of motion. The aim of the simulator designer should be to "mix and match" cuing devices to produce a suitable collection of $S(\omega)$s which match the collection of $A(\omega)$s determined by the mission.

3.4 Task Analysis

3.4.1 Introduction

The task analysis method presented here is intended to help in the development of training equipment and training strategies for the development of skills in piloting aircraft. The fundamental assumption is that any task is, in fact, susceptible to analysis,

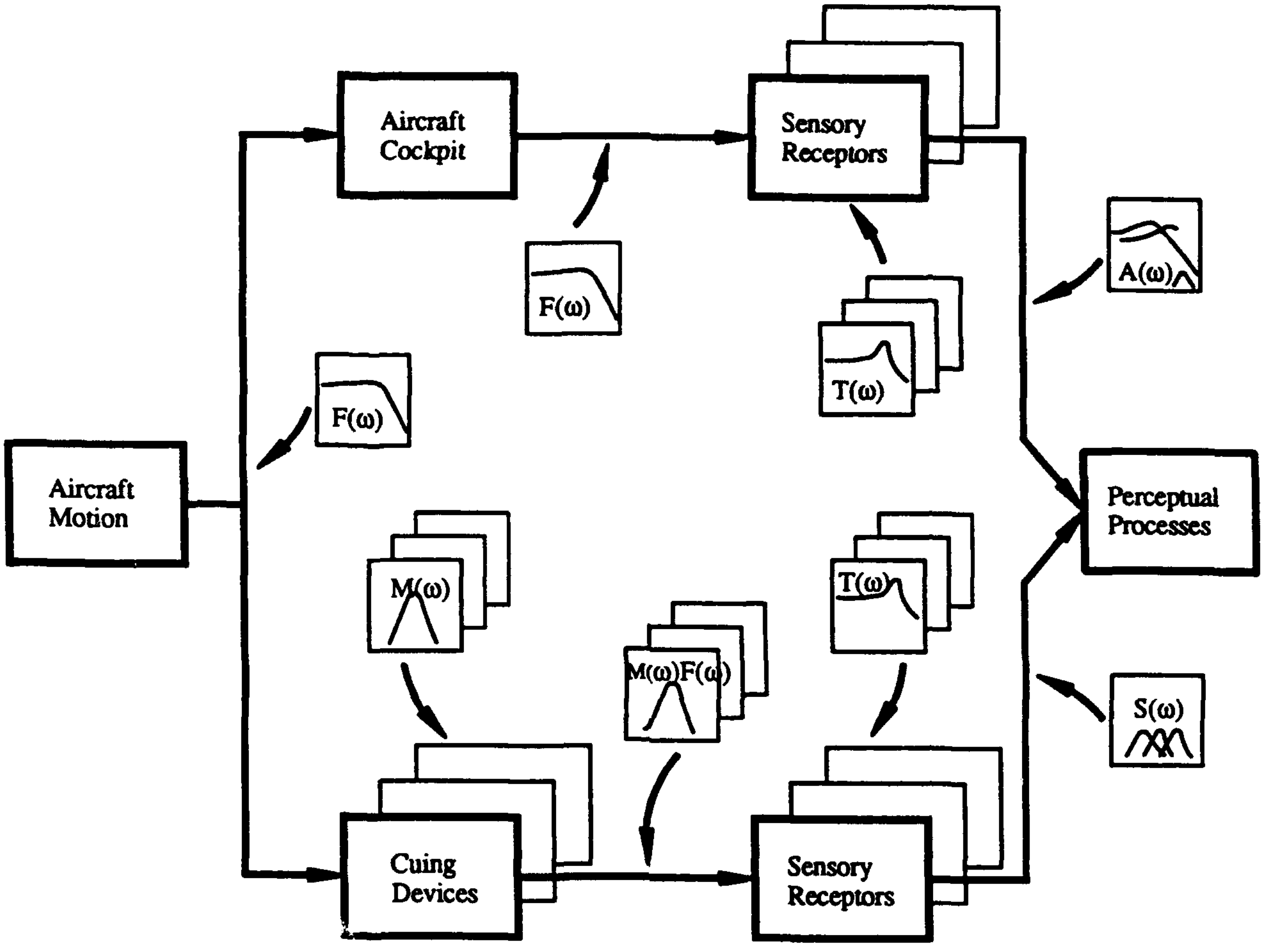

Figure 3.3-1. Block diagram of the signal processing involved in sensation of aircraft motion and simulator motion cues.

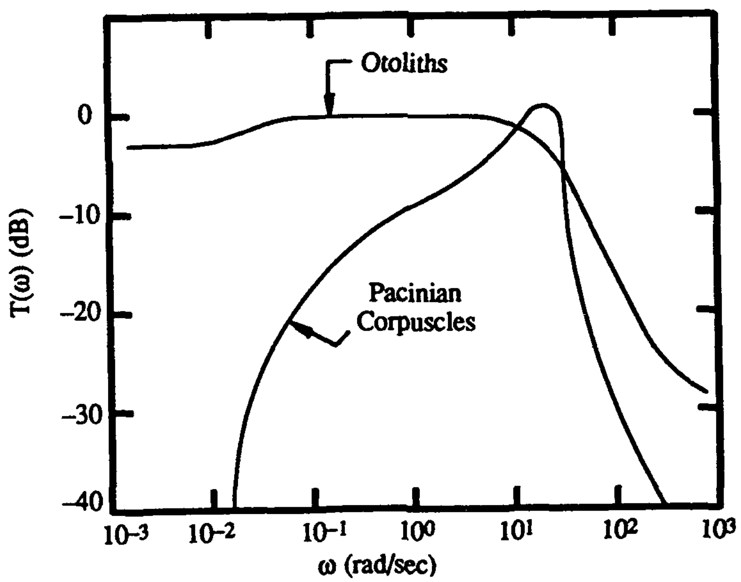

Figure 3.3-2. Frequency responses of the human otoliths and Pacinian corpuscles.

that is, that it can somehow be broken down into components which may be understood individually and as parts of the whole. This assumption implies in turn the further assumption that there exist well defined, named tasks which pilots are trained to perform.

The approach taken develops two types of information about the task under consideration. One aspect is that of the physical motions of the aircraft as it executes the task. This information is necessary both to specify the envelope of capabilities relevant to the trainer, and to identify the physical forces imposed on the pilot and the physical processes the pilot must deal with. The second aspect of the analysis is the derivation of the kinds of information the pilot uses for control and the forms in which they are accessible to him. The purpose of this analysis is to help identify what physiological and sensory effects the trainer should replicate in order to provide effective training.

The analysis itself consists of four parts. First is a verbal description of the task supplemented by any supporting information or commentary necessary to specify what the task is. In the case of the pop-up ground attack maneuver, a planning sheet as described in the F-4 advanced training curriculum is provided along with the verbal description.

The second component of the analysis is a graphical representation of the maneuvers involved in the task. The trajectory of the aircraft is shown in two charts, a plan view and a profile view, showing all the relevant time, distance, altitude, and acceleration data for the task. For the pop-up, this information is presented in Figures 3.5-1 and 3.5-2. Preparation of these figures involves computing the aircraft trajectory through all its maneuvers.

The third element of the analysis is the task analysis summary, a tabular breakdown of the task into its components with a quantitative description of the aircraft state, the pilot's actions, and all the cues, sensory effects and constraints on pilot action which are involved in executing the task. The summary is described in more detail below.

In order to make the analysis a useful tool in studying any specific aspect of the task, "filtered" versions of the summary are prepared. For example, in the analysis presented below, the main area of study is in force and motion effects, so a version of the summary filtered to concentrate on force and motion is also presented.

The fourth component of the analysis is a set of time histories of the four primary state variables used in the spectral analysis of force-and-motion cuing. The state variables treated are

vertical acceleration, pitch rate, longitudinal acceleration, and roll rate. These variables were chosen to provide a complete specification of the accelerations applied to the pilot. The time histories are computed from the same analysis which produced the trajectory plan and profile charts.

3.4.2 Discussion

Pilot actions involve motions which may be relevant to the physiological and physical processes of sensation and constraints on action. For example large head movements in order to track traffic or targets at large angles from the axis of the aircraft may be constrained by high g-loading. Analysis must include descriptions of these actions, and possible references to constraints.

A control task can be analyzed at any level, from the mere identification of a large, complex task, down to the enumeration and description of every possible action. For the purpose of the analytical method developed here, it is convenient to analyze the task itself at the level of the elementary flight maneuvers familiar to every airman. Table 3.4-1 lists these standard, elementary maneuvers.

The state of the aircraft is summarized by giving the values of standard state parameters. The standard state parameters are listed in Table 3.4-2.

3.4.3 The Task Analysis Summary

The complete task analysis is summarized in a table which correlates the elements of the maneuvers to pilot actions and effects on the pilot. An example Task Analysis Summary Table is given in Tables 3.5-2 and 3.5-3.

3.4.3.1 Segment, Time, and State

The task is broken down temporally into well-defined segments. Each segment has clearly identifiable endpoints and, ideally, well-defined aircraft states and state transitions. Segments are identified serially by letter as well as by name. The time the segment begins is given in the TIME column; the duration is shown in the REMARKS area.

The physical motions and state of the aircraft are given by listing the standard maneuvers being executed and the standard state parameters. Constancy of a parameter is indicated by an equals sign; changing values are indicated by less than and greater than signs. For example, "PIT = +20" means that the pitch is constant at 20 degrees nose up; "PIT < +40" means that pitch is increasing from its previous value to 40 degrees nose up.

Table 3.4-1 Standard Maneuvers

SL	Straight and Level
LT	Level Left Turn
RT	Level Right Turn
SC	Straight Ahead Climb
SD	Straight Ahead Descent
TU	Power Up
TD	Power Down
RL	Roll Left
RR	Roll Right
PU	Pitch Up (Pullup)
PD	Pitch Down (Pushover)
RC	Climbing Right Turn
RD	Descending Right Turn
LC	Climbing Left Turn
LD	Descending Left Turn

Table 3.4-2 Standard State Parameters

HDG	(deg)	Heading
PIT	(deg)	Pitch
ROL	(deg)	Roll
PWR		Power (Thrust)
ALT	(ft)	Altitude
TAS	(ft)	True Airspeed
ROC	(ft/sec)	Vertical Speed
TRT	(deg/sec)	Turn Rate
PRT	(deg/sec)	Pitch Rate
GX	(g)	Longitudinal Acceleration (Pilot Body)
GY	(g)	Lateral Acceleration (Pilot Body)
GZ	(g)	Vertical Acceleration (Pilot Body)

3.4.3.2 Pilot Action

For each segment, pilot actions are listed in what amounts to a checklist-style verbal description of the task. The list is organized hierarchically starting with goals which must be accomplished and working down to specific limb motion and sensory organ actions which the pilot executes to achieve his goals. The list of pilot actions serves to identify various problems the pilot must solve in order to complete the task. The analyst should consider the following types of problems:

a. Cognitive problems. What must the pilot do to gather the information about the status that he needs to formulate the situation concept? What estimates, calculations, deductions, inferences, or decisions must he make?

b. Perceptual problems. What senses are available? How effective are they? (This category ties in to the cues, realism effects, and constraints areas of the analysis.)

c. Control problems. What must the pilot do to make the aircraft execute the maneuvers required? What characteristics of the aircraft or its status affect the regulation of control actions? What control errors are likely?

3.4.3.3 Cue Classification

In the summary, cues are classified first according to sensory system and then according to type. The sensory systems addressed are:

a. Visual
b. Vestibular
c. Somatosensory
d. Auditory

Under each of these classifications is a list of cues, organized by cue type. Each cue is described along with its use in the control task. The type of each cue is identified by a two letter code as follows:

OP Overt Primary
OS Overt Secondary
CS Covert Secondary
CF Confusing
XX Complex

In listing cues, it is helpful to consider all the kinds of information the pilot requires to successfully perform the task, and then to identify the cues required to supply the needed information. For each item listed in the PILOT ACTION column, there should be associated cues which the pilot uses to regulate

that action. In addition, the pilot requires information to form a general awareness of the aircraft state, so it is useful to consider including the cues informing the pilot of each element in the STATE column.

3.4.3.4 Other Effect Classification

Other effects are organized in the summary similarly to cues. The list of effects is first classified by sensory system, and then by type. The sensory systems are the same as for cues, but with the addition of a class called cardio-respiratory. The realism effect types and associated codes are as follows:

ST Stressors
RE Realism Effects
CP Cue Potentiators

3.4.3.5 Constraint Classification

Constraints on action are more difficult to classify than cues and other effects, but since there are fewer of them in each segment, they are usually quite easily identified and listed. It is useful to consider the entries in the OTHER EFFECTS column in enumerating constraints.

3.5 Application of the Need-Based Method to a Specific Case: The Pop-Up Attack

3.5.1 Verbal Description of the Task

The complementary problems of gaining aerial access to a target and delivering a weapon on the target are in many ways incompatible. Ingress to the target requires stealth, and stealth implies flight at low level in order to evade detection by the enemy. If the aircraft is detected, then evasion is the key to survival, and evasion involves unpredictable flight maneuvers. Delivery, on the other hand, requires altitude over the target in order to avoid entering one's own "frag envelope," and, for accuracy, requires release of the weapon (a bomb, in this analysis) at a planned, constant dive angle, altitude, and airspeed. The pop-up is a maneuver which makes the transition from a stealthy, low-level ingress to a high altitude delivery with precisely fixed "parameters to drop."

Planning for a pop-up begins with considering the tactical problems of objective and target. For this example, the problem is to use an F-4 fighter to deliver a single MK-82 LDGP bomb from a 30 degree attack angle at 540 KTAS. To keep the problem simple, it is assumed that there is no wind or terrain to deal with. Weapons characteristics and ballistics tables give a reasonable release altitude (RLA) of 3000 feet AGL and a bomb range (BRG) of 4272 feet. The selected RLA will allow clearance

of the frag envelope if the pilot pulls 4 G within 2 seconds after release. He can expect to lose about 1600 feet during pullout to bottom out at a minimum recovery altitude (MRA) of 1400 feet AGL. The aircrew requires 4 seconds of track time (TKT) to stabilize the attack after arriving in the target area. These parameters basically fix the attack and escape portion of the maneuver, and define a circle around the target (the minimum attack perimeter, or MAP) from which the attack commences. The rest of the maneuver is designed to take the aircraft from an initial approach altitude (IAA) of 500 feet AGL, to the track point (TKP) which lies at a selected spot on the minimum attack perimeter.

3.5.2 Graphical Representation of the Maneuvering

After flying a carefully planned ingress route at about 500 ft AGL, the pilot begins the maneuver proper by crossing directly over a planned point called the pull-up point (PUP) and pulling into a steep climb. Using the standard planning formulas shown in Table 3.5-1, the PUP will lie as shown in the plan view of Figure 3.5-1, and the climb angle (CLA) will be 40 degrees. The pop-up itself begins with a smooth pull to a little over 4G and then unloading as the aircraft achieves 40 degrees of pitch. Military power is required to maintain airspeed. Figure 3.5-2 shows a profile of the maneuver. While climbing up to the planned roll in point (RIP), the crew visually searches for and acquires the target, which, in this example will be off the right side of the airplane. Upon reaching the roll in point, the pilot rolls rapidly right while maintaining the climb and places the target in the centerline of the canopy over his head. He will by then have arrived at the pull down point (PDP) where he begins a smooth pull of about 3.5 G, obliquely arcing the airplane over the top of the pop-up and into the 30-degree dive for delivery. In this example, the apex (APX) will occur at about 6300 feet AGL. Crossing the apex, the pilot pulls back the power in order to maintain the required airspeed. During the pull down, the aircraft is nearly inverted (rolled about 130 degrees), and the target will move smoothly down the centerline of the canopy into the HUD. If all has gone properly (and there are many factors which may disrupt the maneuver), the target will center in the HUD with the aircraft pitched down 30 degrees about one second's flying time outside the MAP. The pilot quickly selects an aim-off point (AOP), fixes it in his window, and rolls about it back to wings level. The target should pendulum into place in the HUD below the AOP and below the pipper, which the pilot has placed to accurately aim the bomb when he has achieved the parameters to drop. Again, if all has gone well, the aircraft has just passed the track point pointed toward the AOP in a 30-degree dive at 540 KTAS. The pilot has four seconds to maneuver the aircraft to correct any discrepancies in flight path and stabilize the attack. During the tracking period, he maneuvers to make the target move smoothly into the pipper just

at the release point, where he pickles off the bomb, and executes the pullout for recovery.

Figure 3.5-2 gives all the altitudes, distances, times, major G_z levels, and turn radii for a textbook perfect pop-up. These figures are used as the basis for the aircraft state data in Table 3.5-2 and the time histories given in Figure 3.5-3.

This analysis provides a sound basis for preparing a spectral analysis of the forces and accelerations involved in the pop-up, but it must be emphasized that in real life, the actual maneuver is executed based on what the pilot sees from the cockpit as much as on what he has planned. The successful dive bomber is one who can maneuver his aircraft close to the planned trajectory, but who also can effectively correct for the discrepancies which inevitably arise. Achieving the desired trajectory is not so much a matter of executing a canned sequence of actions as it is effectively visualizing the planned trajectory in the air above the target and then maneuvering the airplane to follow it. The skilled dive bomber visualizes the "wire"--the final tracking flightpath--while still in the climbout. He plans the pulldown to put his craft on the wire, cross checking altitude at the critical points to help him anticipate how successful he will be and what later corrections he will need to make. He may also make use of ground references other than the target if his planning (or his experience at the range) has been thorough enough. The range of trajectories for a typical pop-up, however, should result in essentially identical force and motion spectra.

3.5.3 Task Analysis Summary

The results of the task analysis on the pop-up attack are summarized in Table 3.5-2. Table 3.5-3 is a "filtered" version of Table 3.5-2. It includes only those cues, other sensory effects, and constraints that might be simulated with potential CUMOD devices.

TABLE 3.5-1. POP-UP PLANNING WORKSHEET

Aircraft	:	F-4E
Weapon	:	MK82 LDGP Bomb
Attack Speed	:	540 KTAS = 911 FPS
Dive angle	:	30 deg
Initial approach altitude	:	500 AGL
Track Time	:	4 sec

Parameter	Symbol	Source	Value
Dive Angle	DVA	Tactics	30 deg
Airspeed at Release	TAS	Tactics	911 fps
Initial Approach Altitude	IAA	Tactics	500 ft
Release Altitude	RLA	Dash-34	3000 ft
Bomb Range	BRG	Dash-34	4272 ft
Track Time	TKT	Tactics	4 sec
Slant Track Distance	STD	= TAS*TKT	3644 ft
Horizontal Track Distance	HTD	= STD*cos(DVA)	3156 ft
Vertical Track Distance	VTD	= STD*sin(DVA)	1822 ft
Minimum Attack Distance	MAD	= BRG+HTD	7428 ft
Track Point Altitude	TPA	= RLA+VTD	4822 ft
Roll Out Distance (1 sec)	ROD	= TAS*cos(DVA)	789 ft
Roll Out Altitude	ROA	= TPA+TAS*sin(DVA)	5278 ft
Apex Altitude	AXA	= TPA+50*DVA	6322 ft
Climb Angle	CLA	= DVA+10	40 deg
Optimum Angle-Off	OAO	= 2*CLA	80 deg
Pull Down Altitude	PDA	= AXA-(50*CLA)	4322 ft
Roll In Altitude (1 sec)	RIA	= PDA-TAS*sin(CLA)	3736 ft
PUP to PDP Distance	PUD	= (AXA-IAA)*(60/CLA) -150*(IAA/100)	7983 ft

Other Symbol Definitions

Pull Up Point	PUP	A/R	As required
Roll In Point	RIP	ASI	Air speed indicator
Pull Down Point	PDP	ETA	Estimated time of arrival
Apex	APX	AGL	Above ground level
Roll Out Point	ROP	DR	Dead reckoning
Track Point	TKP	INS	Inertial navigation system
Minimum Attack Perimeter	MAP	ECM	Electronic counter measures
Release Point	RLP	AC	Centriptal acceleration (g)
Target	TGT	AI	Attitude indicator
Aim Off Point	AOP	HUD	Head up display
Minimum Recovery Point	MRP	IAS	Indicated airspeed

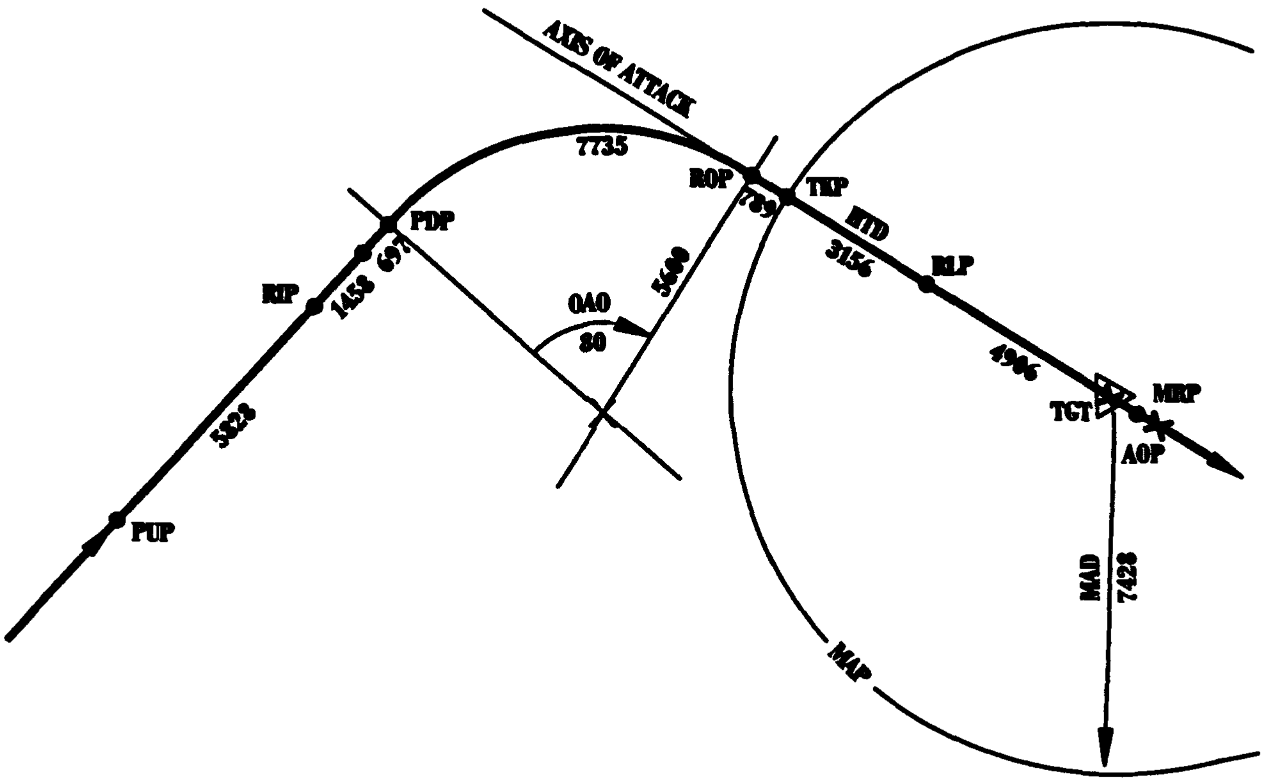

Figure 3.5-1. Pop-Up Maneuver Plan View.

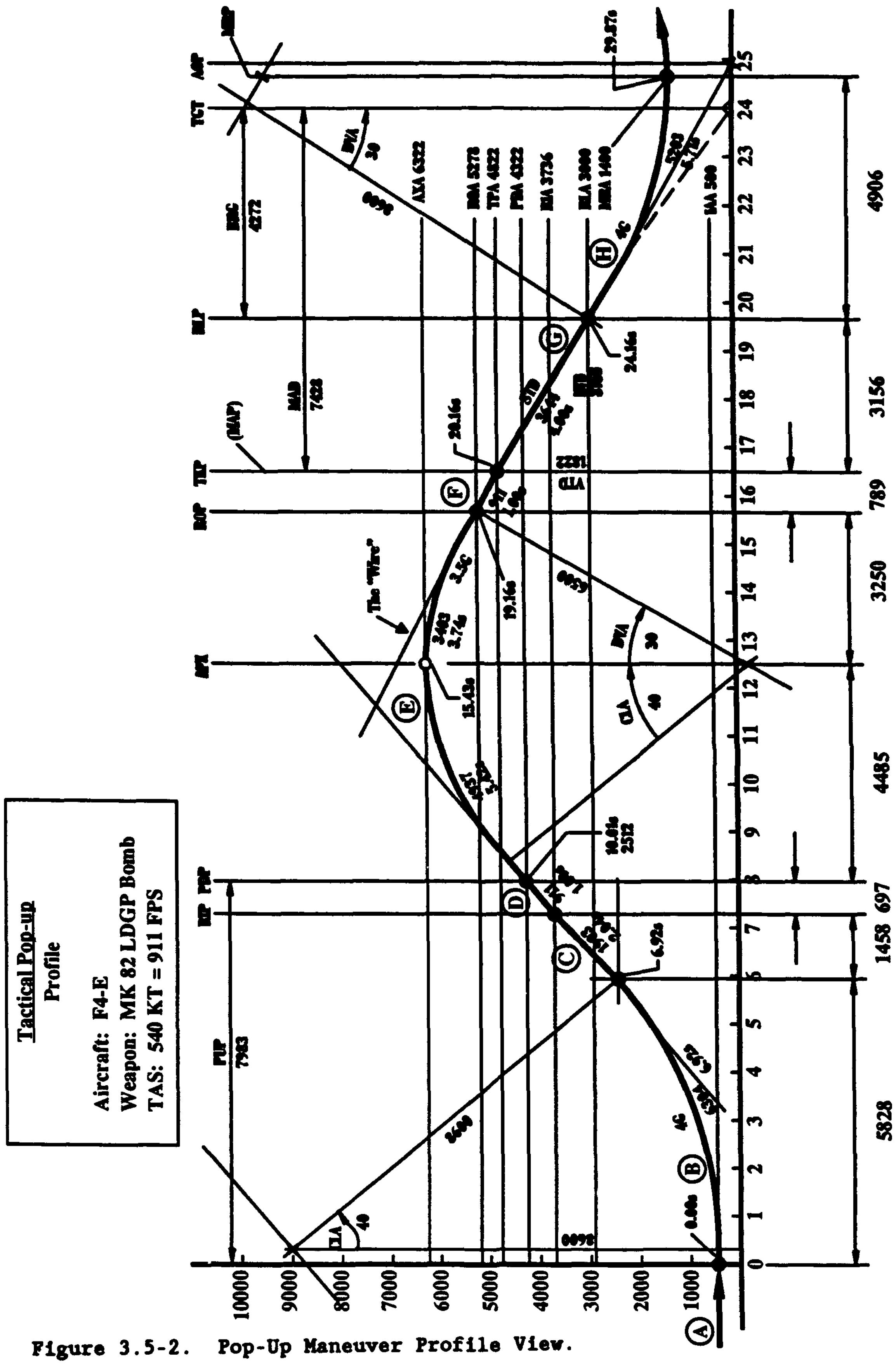

Figure 3.5-2. Pop-Up Maneuver Profile View.

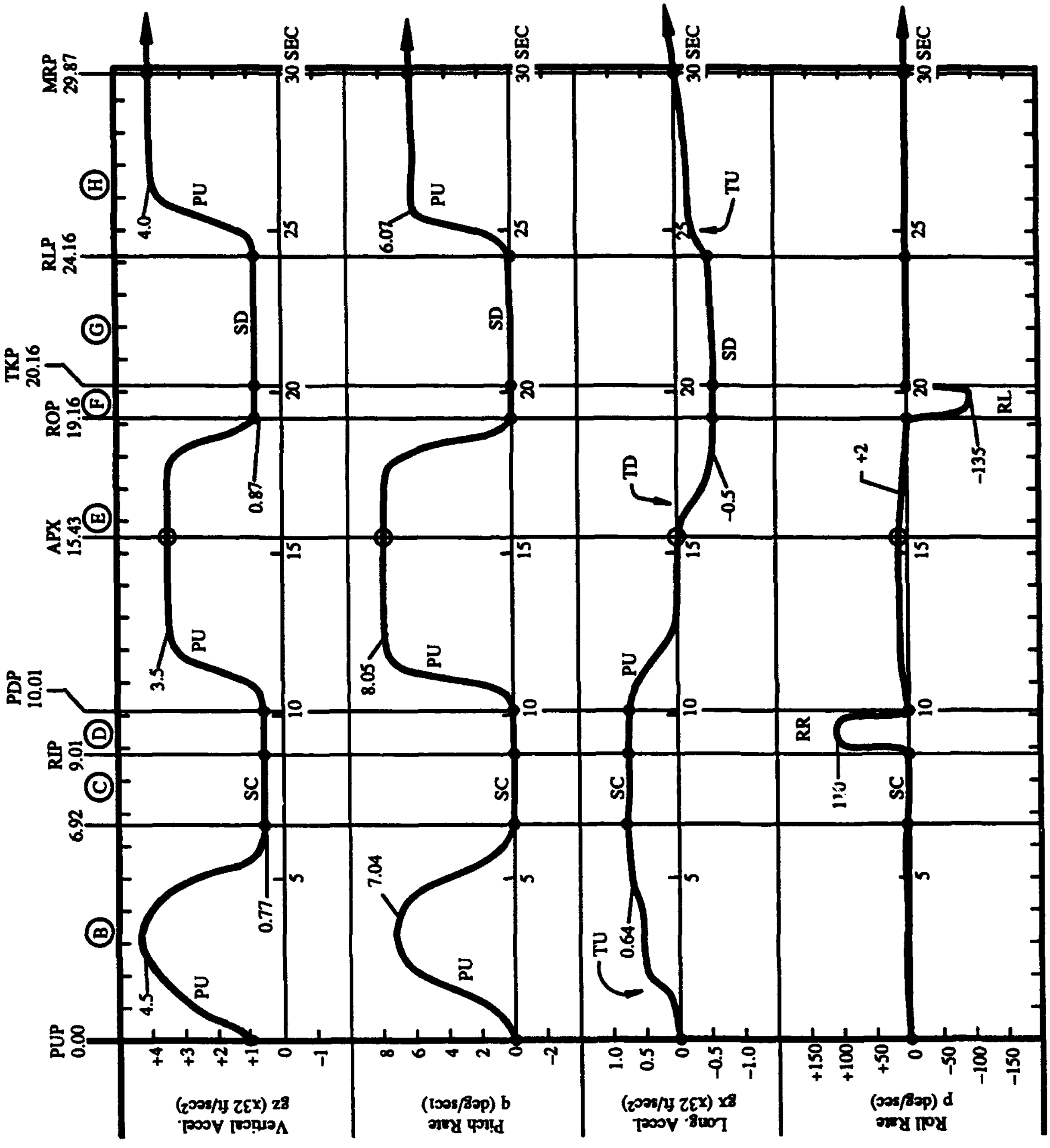

Figure 3.5-3. Pop-Up Maneuver Time Histories.

Table 3.4-1 Standard Maneuvers

SL	Straight and Level
LT	Level Left Turn
RT	Level Right Turn
SC	Straight Ahead Climb
SD	Straight Ahead Descent
TU	Power Up
TD	Power Down
RL	Roll Left
RR	Roll Right
PU	Pitch Up (Pullup)
PD	Pitch Down (Pushover)
RC	Climbing Right Turn
RD	Descending Right Turn
LC	Climbing Left Turn
LD	Descending Left Turn

Table 3.4-2 Standard State Parameters

HDG	(deg)	Heading
PIT	(deg)	Pitch
ROL	(deg)	Roll
PWR		Power (Thrust)
ALT	(ft)	Altitude
TAS	(ft)	True Airspeed
ROC	(ft/sec)	Vertical Speed
TRT	(deg/sec)	Turn Rate
PRT	(deg/sec)	Pitch Rate
GX	(g)	Longitudinal Acceleration (Pilot Body)
GY	(g)	Lateral Acceleration (Pilot Body)
GZ	(g)	Vertical Acceleration (Pilot Body)

Table 3.5-2. Task Analysis Summary Table

F-4 Pop-Up Ground Attack

SEGMENT	TIME	STATE	PILOT ACTION	CUES	SENSORY EFFECTS	CONSTRAINT
A Initial approach	> 0	SL HDG=360 PIT = 0 ROL = 0 PWR=A/R ALT=500 TAS=540 ROC = 0 PRT = 0 RRT = 0 GX = 0 GZ = +1	.Correct deviations from SL using stick -Small right arm motion .Select power to stabilize airspeed at 540 KTAS -Left arm motion on throttle -Eye motion to read ASI .Search for PUP (or monitor for ETA -Small head motions -Scanning eye motions .Acquire and identify PUP -Pursuit eye motions -Large pitch down of head and eye to check map .Maintain visual lookout for threats -Large head motions in yaw -Scanning eye motions	<u>Visual</u> .OP:Horizon for attitude .OP:Altimeter for ALT .OP:Clock for ETA .XX:Ground scenery for pilotage to PUP .OS:Motion of visual scene (ground rush) <u>Vestibular</u> .CS:Roll sensations for roll onset (used to correct deviations from SL) .CS:Pitch sensations for pitch onset (used to correct deviations from SL) <u>Somatosensory</u> .None significant <u>Auditory</u> .None significant	<u>Vestibular</u> .None Significant <u>Somatosensory</u> RE:Vibration .CP:Small bodily accelerations <u>Auditory</u> .RE:Engine and slipstream sounds <u>Cardio-Respiratory</u> .None significant	None
			REMARKS: 540 KTAS = 911 FPS Object is to arrive exactly over the PUP with 540 KTAS heading 360 altitude 500 AGL. Normally, navigation is by pilotage but with DR and INS to reserve.			

SEGMENT	TIME	STATE	PILOT ACTION	CUES	SENSORY EFFECTS	CONSTRAINT
B Pull up at PUP	0.0	PU,TU HDG = 360 PIT < +40 ROL = 0 PWR = MIL ALT<2512 TAS = 540 ROC < 586 PRT= +6.1 RRT = 0 GX < +.64 GZ = +4	.Stick back to4G -Right arm motion .Military power -Left arm motion .Correct deviations to maintain wings level -Small lateral right arm motions -Lateral head and eye motions .Initiate ECM Pod -Left Arm motion to switches .Release back pressure at 40 deg nose up -Right arm motion	Visual .OP:Horizon for attitude .OS:AI or HUD for pitch cross reference Vestibular .CS:Roll sensations for roll onset (used to correct deviations from wings level) .CS:Pitch sensations for pitch onset (used to correct deviations from desired path) Somatosensory .CS:Stick force for control regulation .OP:Throttle detent for power control Auditory .None Significant	Visual .CP:Motion of visual scene Vestibular .CP:Pitch up sensation Somatosensory .CP:Gz Effects -Seat Pressure -Back scrubbing .ST:Gz Effects -Head and Limb weight -Mask sag Auditory .CP:Engine and slipstream sounds Cardio-Respiratory .Re:Gz Effects -G-Suit inflation .ST:Gz Effects -Reduced eye-level blood pressure; possible g-dimming -Increased breathing effort	.Limb heaviness .Head heaviness .Breathing difficulty
			REMARKS: A_c = 3G Turn Radius = 8600 GZ peaks at 4.5 PRT peaks at 7.04 G-dimming is unlikely, but if it occurs, the pilot may use it as a pitch control cue. Severe g-dimming is a constraint. 6.92 sec			

SEGMENT	TIME	STATE	PILOT ACTION	CUES	SENSORY EFFECTS	CONSTRAINT
C Climb out and acquire target	6.9	SC HDG = 360 PIT = +40 ROL = 0 2WR = A/R ALT< 3736 TAS = 540 ROC = 586 PRT = 0 RRT = 0 GX = +.64 GZ = +77	.Correct deviations from SL with stick -Small right arm motion .Adjust power to maintain airspeed at 540 KTAS -Left arm motion on throttle -Eye motion to read ASI .Monitor ALT -Eye motion to read ALT .Search for TGT -Small head motion -Scanning eye motions .Acquire and identify TGT -Pursuit eye motions .Maintain visual lookout for threats -Large head motions in yaw -Scanning eye motions .Select AOP	Visual .OP:Horizon for attitude .OS:HUD for pitch cross reference .OP:ASI for power .XX:Ground scenery for target acquisition .OP:Altimeter for endpoint Vestibular .CS:Roll sensations for roll onset (used to correct deviations from wings level) .CS:Pitch sensations for pitch onset (used to correct deviations from desired path) Somatosensory .None significant Auditory .None significant	Visual .RE:Complexity of visual scene complicates target acquisition Vestibular .None Significant Somatosensory .RE:Vibration .CP:Small bodily accelerations Auditory .RE:Engine and Cardio-Respiratory .None significant	None
			REMARKS: Pilot must stay alert for threats as well as locate target. RIA = 3736 2.09 sec			

SEGMENT	TIME	STATE	PILOT ACTION	CUES	SENSORY EFFECTS	CONSTRAINT
D Roll in toward target	9.0	SC,RR HDG = 360 PIT = +40 ROL< +105 PWR = A/R ALT< 4322 TAS = 540 ROC = 586 PRT = 0 RRT= +110 GX = +.64 GZ = +.77	.Add right aileron for rapid roll rate -Lateral motion of right arm .Maintain 40 deg pitch attitude .Stop roll when AOP is in vertical plane of aircraft -Large head motion in pitch up and yaw during roll -Pursuit eye movement	Visual .OP:Image of target area relative to canopy structure .OS:Horizon for general attitude awareness .CS:Motion of ground scenery in peripheral vision for roll rate Vestibular .CS:Roll sensation to regulate roll rate Somatosensory .CS:Stick force for control regulation Auditory .None Significant	Visual .None Significant Vestibular .None Significant Somatosensory .RE:Postural response to roll Auditory .None Significant Cardio-Respiratory .None Significant	.Head and upper body side load requires bracing
			REMARKS: Bank angle is selected to put target in aircraft vertical plane. For OAO=80deg, ROL = 105 deg at PDP, increasing to about 130 deg approaching ROP Analysis ignores GY effects due to pilot offset from aircraft roll axis. 1.00 sec			

SEGMENT	TIME	STATE	PILOT ACTION	CUES	SENSORY EFFECTS	CONSTRAINT
E Pull down toward target	10.0	PU, TD HDG < 080 PIT > -30 ROL= +135 PWR > A/R ALT< 6322 > 5278 TAS = 540 ROC> -456 PRT= +7.6 RRT = +2 GX > -.50 GZ = +3.5	.Stick back -Arm motion .Use aileron to keep AOP on cockpit centerline -Small arm motion -Large head pitch attitude -Pursuit eye motions .Check for AXA -Eye and head motion to real ALT .Reduce power after apex to maintain 540 KTAS (IAS precomputed) -Left arm motion -Large head and eye motions in pitch to read altimeter and ASI .Release back pressure as AOP centers in HUD -Right arm motion	<u>Visual</u> .OP:Visual direction to the AOP as it moves down the centerline of the cockpit to the HUD for roll control .DS:Horizon for general attitude awareness <u>Vestibular</u> .CS:Roll sensations for roll onset (used to correct deviations from desired path) .CS:Pitch sensations for pitch onset (used to correct deviations from desired path) <u>Somatosensory</u> .CS:Stick force for control regulation <u>Auditory</u> .None significant	<u>Visual</u> .ST:Sense of disorientation due to inverted attitude <u>Vestibular</u> .ST:Sense of disorientation may be complicated by slight coriolis effect .CP:Pitch up sensation <u>Somatosensory</u> .CP:Gz Effects -Seat pressure -Back scrubbing .ST:Gz Effects -Head and Limb weight -Mask sag <u>Auditory</u> .RE:Engine and slipstream sounds <u>Cardio-Respiratory</u> .RE:Gz Effects -G-Suit inflation .ST:Gz Effects -Reduced eye-level blood pressure; possible g-dimming -Increased breathing effort	.Head heaviness constrains target tracking at high angles .Limb heaviness .Breathing difficulty
			REMARKS: This segment smoothly follows previous. Pitch up in A/C body coords results in pitch down in earth coords due to inversion of aircraft. Roll gradually increases to 130 deg. Ideal flight path is elliptical in elevation and plan, but approximatley circular with radius 6500 ft in either view. A_c = 3.0G (approx) G-dimming is unlikely, but if it occurs, the pilot may use it as a pitch control cue. Severe g-dimming is a constraint. 9.16 sec (5.42 sec to APX)			

<table>
<tr><th>SEGMENT</th><th>TIME</th><th>STATE</th><th>PILOT ACTION</th><th>CUES</th><th>SENSORY EFFECTS</th><th>CONSTRAINT</th></tr>
<tr><td rowspan="2">F

Roll out wings level</td><td rowspan="2">19.2</td><td rowspan="2">SD,RL

HDG = 080
PIT = 30
ROL > 0
PWR = A/B
ALT> 4822
TAS = 540
ROC= -456
PRT = 0
RRT= -135
GX = .50
GZ = +.87</td><td>.Add left aileron for rapid roll rate
-Right arm motion
.Use stick to keep AOP centered in HUD
-Right arm motion
-Small pursuit eye motion
.Stop roll when wings level</td><td><u>Visual</u>
.OP:AOP position in HUD for pitch control
.OS:Horizon for general attitude awareness
.CS:Motion of ground scenery in peripheral vision for roll rate
<u>Vestibular</u>
.CS:Roll sensation to regulate roll rate .CS:Pitch sensations for pitch onset (used to correct deviations from desired path)
<u>Somatosensory</u>
.CS:Stick force for control regulation
<u>Auditory</u>
.None significant</td><td><u>Visual</u>
.None Significant
<u>Vestibular</u>
.None Significant
<u>Somatosensory</u>
.RE:Postural response to roll
<u>Auditory</u>
.None Significant
<u>Cardio-Respiratory</u>
.None significant</td><td>.Head and upper body side loading requires bracing</td></tr>
<tr><td colspan="4">REMARKS: Want to get wings level by TKP (crossing MAP).
Roll about the AOP; TGT should pendulum into position above pipper.

Analysis ignores GY effects due to pilot offset from aircraft roll axis.
1.0 sec</td></tr>
</table>

SEGMENT	TIME	STATE	PILOT ACTION	CUES	SENSORY EFFECTS	CONSTRAINT
G Track to release point	20.2	SD HDG = 080 PIT = -30 ROL = 0 PWR = A/R ALT> 3000 TAS = 540 ROC= -456 PRT = 0 RRT = 0 GX = .50 GZ = +.87	.Adjust power for 540 KTAS -Left arm motion .Cross check dive angle .Make slight check -These actions involve multiple eye fixations to check the instruments involved .Track toward target: use stick to correct deviations from desired flight path -Right arm motions .Pickle to release bomb at RLP -Right index finger motion	Visual .OP:Pipper position relative to TGT for flightpath assessment .OS:Horizon for general attitude awareness .OP:Indicator lights for bomb release indication Vestibular .CS:Roll sensation for roll onset (used to correct for deviations from SD) .CS:Pitch sensations for pitch onset (used to correct for deviations from SD) Somatosensory .OP:Pickle switch detent for bomb release timing Auditory .None significant	Visual .RE:Complexity of visual scene complicates target acquisition Vestibular .None Significant Somatosensory .RE:Vibration .RE:Bomb release "unloading" .CP:Small bodily accelerations Auditory .RE:Engine sounds Cardio-Respiratory .None significant	None
			REMARKS: Pilot tracks to the AOP and observes TGT motion toward pip[illegible]. Objective is to get -30 deg pitch 540 KTAS pipper on target pickle all at RLA of 3000 AGL. 4.0 sec (= TKT)			

SEGMENT	TIME	STATE	PILOT ACTION	CUES	SENSORY EFFECTS	CONSTRAINT
H Pull out	24.2 MRP at 29.9	PU,TU HDG = 080 PIT < 0 ROL = 0 PWR = A/R ALT> 1400 TAS = 540 ROC > 0 PRT= +6.1 RRT = 0 GX < 0 GZ = +4.0	.Stick back to 4G in 2 sec -Right arm motion .Use aileron to keep wings level -Small lateral right arm motions -Lateral head and eye motions	Visual .OP:G-meter for pitch control .OS:Horizon for general attitude awareness Vestibular .CS:Roll sensation for roll onset (used to correct deviations from wing level) .CS:Pitch sensations for pitch onset (used to correct for deviations from desired path) Somatosensory .CS:Stick force for control regulation Auditory .None significant	Visual CP:Motion of visual scene (ground rush) Vestibular .CP:Pitch up sensation Somatosensory .CP:Gz Effects -Seat pressure -Back scrubbing .ST:Gz Effects -Head and Limb weight -Mask sag Auditory .RE:Engine and slipstream sounds .RE:Weapons effect sounds Cardio-Respiratory .Re:Gz Effects -G-Suit inflation .ST:Gz Effects -Reduced eye-level blood pressure; possible g-dimming -Increased breathing effort	.Head heaviness .Limb heaviness .Breating difficulty
			REMARKS: Immediately after pickle, pilot pulls 4G in 2 sec and holds util PIT = +30 (analysis extends only to MRP, where PIT=0). The MRP is roughly over the impact area. G-dimming is unlikely, but if it occurs, the pilot may use it as a pitch control cue. Severe g-dimming is a constraint. 5.71 sec			

Table 3.5-3. Task Analysis Summary
F-4 Pop-Up Ground Attack
Filtered for Force and Motion

SEGMENT	TIME	STATE	PILOT ACTION	CUES	SENSORY EFFECTS	CONSTRAINT
A Initial approach	< 0	SL HDG = 360 PIT = 0 ROL = 0 PWR = A/R ALT = 500 TAS = 540 ROC = 0 PRT = 0 RRT = 0 GX = 0 GZ = +1	.Correct deviations from SL using stick -Small right arm motion .Select power to stabilize airspeed at 540 KTAS -left arm motion on throttle -Eye motion to read ASI .Search for PUP (or monitor for ETA) -Small head motions -Scanning eye motions .Acquire and identify PUP -Pursuit eye motions -Large pitch down of head and eye to check map .Maintain visual lookout for threats -Large head motions in yaw -Scanning eye motions	Visual .Horizon for attitude (correlates with vestibular) Vestibular .Roll sensation for roll onset (used to correct deviations from SL) .Pitch sensations for pitch onset (used to correct deviations from SL)	Somatosensory .Vibration .Small bodily accelerations	None
			REMARKS: 540 KTAS = 911 FPS Object is to arrive exactly over the PUP with 540 KTAS heading 360 altitude 500 AGL.			

Table 3.5-3. Task Analysis Summary
F-4 Pop-Up Ground Attack
Filtered for Force and Motion

SEGMENT	TIME	STATE	PILOT ACTION	CUES	SENSORY EFFECTS	CONSTRAINT
B Pull up at PUP	0,0	PU,TU HDG = 360 PIT < +40 ROL = 0 PWR = MIL ALT< 2512 TAS = 540 ROC < 586 PRT= +6.1 RRT = 0 GX < +.64 GZ = +4	.Stick back to 4G -Right arm motion .Military power .Left arm motion .Correct deviations to maintain wings level -Small lateral right arm motions -Lateral head and eye motions .Initiate ECM Pod -Left Arm motion to switches .Release back pressure at 40 deg nose up -Right arm motion	<u>Visual</u> .Horizon for attitude (correlates with vestibular) <u>Vestibular</u> .Roll sensation for roll onset (used to correct deviations from wing level) .Pitch sensations for pitch onset (used to correct deviations from desired path)	<u>Vestibular</u> .Pitch up sensation <u>Somatosensory</u> .Gz Effects -Seat Pressure -Back scrubbing -Head and Limb weight -Mask sag <u>Cardio-Respiratory</u> .Gz Effects -G-Suit inflation -Reduced eye-level blood pressure; possible g-dimming -Increased breathing effort	.Limb heaviness .Head heaviness .Breathing difficulty
			REMARKS: A_c = 3G Turn Radius = 8600 GZ peaks at 4.5 PRT peaks at 7.04 G-dimming is unlikely, but if it occurs, the pilot may use it as a pitch control cue. Severe g-dimming is a constraint. 6.92 sec			

SEGMENT	TIME	STATE	PILOT ACTION	CUES	SENSORY EFFECTS	CONSTRAINT
C Climb out and acquire target	6.9	SC HDG = 360 PIT = +40 ROL = 0 PWR = A/R ALT< 3736 TAS = 540 ROC = 586 PRT = 0 RRT = 0 GX = +.64 GZ = +.77	.Correct deviations fromSC with stick -Small right arm motion .Adjust poiwer to maintain airspeed at 540 KTAS -Left arm motion on throttle -Eye motion to read ASI .Monitor ALT -Eye motion to read ALT .Search for TGT -Small head motions -Scanning eye motions .Acquire and identify TGT -Pursuit eye motions .Maintain visual lookout for threats -Large head motions in yaw -Scanning eye motions .Select AOP	Visual .Horizon for attitude (correlates with vestibular) Vestibular .Roll sensations for roll onset (used to correct deviations from wings level) .Pitch sensations for pitch onset (used to correct deviations from desired path)	Somatosensory .Vibration .Small bodily accelerations	None
			REMARKS: RIA = 3736 2.09 sec			

SEGMENT	TIME	STATE	PILOT ACTION	CUES	SENSORY EFFECTS	CONSTRAINT
D Roll in toward target	9.0	SC,RR HDG = 360 PIT = +40 ROL< +105 PWR = A/R ALT< 4322 TAS = 540 ROC = 586 PRT = 0 RRT= +110 GX = +.64 GZ = +.77	.Add right aileron for rapid roll rate -Lateral motion of right arm .Maintain 40 deg pitch attitude .Stop roll when AOP is in vertical plane of aircraft -large head motion in pitch up and yaw during roll -Pursuit eye movement	Visual .Horizon for general attitude awareness (correlates with vestibular) .Motion of ground scenery in peripheral vision for roll rate (correlates with vestibular) Vestibular .Roll sensation to regulate roll rate	Somatosensory .Postural response to roll	.Head and upper body side load requires bracing
			REMARKS: Bank angle is selected to put target in aircraft vertical plane. For OAO=80deg, ROL = 105 deg at PDP, increasing to about 130 deg approaching ROP Analysis ignores GY effects due to pilot offset from aircraft roll axis. 1.00 sec			

SEGMENT	TIME	STATE	PILOT ACTION	CUES	SENSORY EFFECTS	CONSTRAINT
E Pull down toward target	10.0 Apex at 15.4	PU,TD HDG < 080 PIT > -30 ROL= +135 PWR > A/R ALT< 6322 > 5278 TAS = 540 ROC> -456 PRT= +7.6 RRT = +2 GX > -.50 GZ = +3.5	.Stick back -Arm motion .Use aileron to keep AOP on cockpit centerline -Small arm motion -Large head pitch attitude -Pursuit eye motions .Check for AXA -Eye and head motion to read ALT .Reduce power after apex to maintain 540 KTAS (IAS precomputed) -Left arm motion -Large head and eye motions in pitch to read altimeter and ASI .Release back pressure as AOP centers in HUD -Right arm motion	<u>Visual</u> .Horizon for general attitude awareness (correlates with vestibular) <u>Vestibular</u> .Roll sensations for roll onset (used to correct deviations from desired flight path) .Pitch sensations for pitch onset (used to correct deviations from desired path)	<u>Visual</u> .Sense of disorientation due to inverted attitude <u>Vestibular</u> .Sense of disorientation may be complicated by slight coriolis effect .Pitch up sensation <u>Somatosensory</u> .Gz Effects -Seat Pressure -Back scrubbing -Head and Limb weight -Mask sag <u>Cardio-Respiratory</u> .Gz Effects -G-Suit inflation -Reduced eye-level blood pressure; possible g-dimming -Increased breathing effort	.Head heaviness constrains target tracking at high angles .Limb heaviness .Breathing difficulty
			REMARKS: This segment smoothly follows previous. Pitch up in A/C body coords results in pitch down in earth coords due to inversion of aircraft. Roll gradually increases to 130 deg. Ideal flight path is elliptical in elevation and plan, but approximately circular with radius 6500 ft in either view. G-dimming is unlikely, but if it occurs, the pilot may use it as a pitch control cue. Severe g-dimming is a constraint. A_c = 3.0 (approx) 9.16 sec (5.42 sec to APX)			

SEGMENT	TIME	STATE	PILOT ACTION	CUES	SENSORY EFFECTS	CONSTRAINT
F Roll out wings level	19.2	SD,RL HDG = 080 PIT = -30 ROL > 0 PWR = A/R ALT> 4822 TAS = 540 ROC= -456 PRT = 0 RRT= -135 GX = -.50 GZ = +.87	.Add left aileron for rapid roll rate -Right arm motion .Use stick to keep AOP centered in HUd -Right arm motion -Small pursuit eye motion .Stop roll when wings level	Visual .Horizon for general attitude awareness (correlates with vestibular) .Motion of ground scenery in peripheral vision for roll rate (correlates with vestibular) Vestibular .Roll sensations to regulate roll rate .Pitch sensations for pitch onset (used to correct deviations from desired path)	Somatosensory .Postural response to roll	.Head and upper body side loading requires bracing
			REMARKS: Want to get wings level by TKP (crossing MAP). Analysis ignores GY effects due to pilot offset from aircraft roll axis. 1.0 sec			

SEGMENT	TIME	STATE	PILOT ACTION	CUES	SENSORY EFFECTS	CONSTRAINT
G Track to release point	20.2	SD HDG = 080 PIT = -30 ROL = 0 PWR = A/R ALT> 3000 TAS = 540 ROC= -456 PRT = 0 RRT = 0 GX = -.50 GZ = +.87	.Adjust power for 540 KTAS -Left arm motion .Cross check dive angle .Make sight check -These actions involve multiple eye fixations to check the instruments involved .Track toward target: use stick to correct deviations from desired flight path -Right arm motions .Pickle to release bomb at RLP -Right index finger motion	<u>Visual</u> .Horizon for general attitude awareness (correlates with vestibular) <u>Vestibular</u> .Roll sensation for roll onset (used to correct for deviations from SD) .Pitch sensations for pitch onset (used to correct deviations from SD)	<u>Somatosensory</u> .Vibration .Bomb release "unloading" .Small bodily accelerations	None
			REMARKS: Objective is to get -30 deg pitch 540 KTAS pipper on target pickle all at RLA of 3000 AGL. 4.0 sec (= TKT)			

SEGMENT	TIME	STATE	PILOT ACTION	CUES	SENSORY EFFECTS	CONSTRAINT
H Pull out	24.2 MRP at 29.9	PU,TU HDG = 080 PIT < 0 ROL = 0 PWR = A/R ALT> 1400 TAS = 540 ROC > 0 PRT= +6.1 RRT = 0 GX < 0 GZ = +4.0	.Stick back to 4G in 2 sec -Right arm motion .Use aileron to keep wings level -Small lateral right arm motions -Lateral head and eye motions	<u>Visual</u> .Horizon for general attitude awareness (correlates with vestibular) <u>Vestibular</u> .Roll sensations for roll onset (used to correct deviations from wings level) .Pitch sensations for pitch onset (used to correct deviations from desired path)	<u>Vestibular</u> .Pitch up sensation <u>Somatosensory</u> .Gz Effects -Seat pressure -Back scrubbing -Head and Limb weight -Mask sag <u>Cardio-Respiratory</u> .Gz Effects -G-Suit inflation -Reduced eye-level blood pressure; possible g-dimming -Increased beathing effort	.Head heaviness .Limb heaviness .Breathing difficulty
			REMARKS: Immediately after pickle, pilot pulls 4G in 2 sec and holds until PIT = +30 (analysis extends only to MRP, where PIT=0). The MRP is rougly over the impact area. G-dimming is unlikely, but if it occurs, the pilot may use it as a pitch control cue. Severe g-dimming is a constraint. 5.71 sec			

3.5.4 Evidence of Cue Relevance

Table 3.5-4 provides a brief discussion of the importance of each of the pilot stimuli included in Table 3.5-3. Empirical evidence that these stimuli are relevant to pilot performance, behavior, training, or subjective responses is indicated by citations of the references listed in Appendix A.

TABLE 3.5-4. Relevant Pilot Stimuli in the Pop-Up Attack

VISUAL

- Horizon for attitude control.

  That pilots use the position of the horizon in the windscreen for attitude control is common knowledge and essentially obvious. How pilots are trained to use the horizon visually is discussed in the FAA Flight Training Handbook (1980) and by Kershner (1987).

  The interaction and interdependence of visual attitude change cues and vestibular motion cues is treated in detail by Young (1977), Zacharias (1977), and Dichgans (1983, 1986).

- Horizon for general attitude awareness.

  Even when the pilot is not consciously using the horizon for precise attitude control, his perceptual system continues to process visual attitude information to maintain an awareness of attitude.

  Since inversion is an unusual attitude for a human, the subconscious use of the horizon may be inadequate for attitude awareness while inverted. See Kershner (1987).

- Motion of ground scenery in peripheral vision.

  The visual periphery appears to be specifically sensitive to retinal field motion (Coren, Porac, and Ward (1984), p. 331). Consequently, the motion of peripheral scenery is important to the pilot's detection and control of roll (through motion of the peripheral scene (Hosman and van der Vaart (1981)), and of ground speed at low altitude through the optical flow field or "ground rush effect." See Owen, et al. (1981), and Wong and Frost (1978). One of the pilots interviewed in the study stated that in low level flight, the ground rush effect is very strong and can be quite alarming. Low level altitude control depends to some extent upon the pilot's emotional response to ground rush. Frequent exposure to ground rush is essential to acclimatize

the pilot to it so that he can retain his ability to fly at tactically effective low altitudes.

- o G-Dimming.

  Although g-dimming is apparent to the pilot as a visual effect, it is physiologically a cardio-respiratory effect. See below.

VESTIBULAR

- o Roll sensations for roll onset.

  The relevance of vestibular sensations for roll onset can be illustrated employing three different principled bases; perceptual fidelity, performance and behavior considerations. In terms of perceptual fidelity, Hung & Young (1988) state that visual cues dominate at low frequencies < .4 Hz, however, for higher frequencies the human relies on vestibular information. Young (1982) indicates that for stimulation frequencies less than 0.1 Hz the semicircular canal output indicates that it acts as an angular acceleration sensor and an angular velocity sensor at higher stimulation frequencies. Many other authors discuss the role of the semicircular canals in the perception of rotary motion (Gundry (1978a), Ormsby (1974), Borah (1977), Dichgans (1986), Fernandez & Goldberg (1971)). With respect to performance effects, the literature is rich with examples that simulator pilot performance is either improved or more like that in the aircraft in the presence of vestibular stimulation. (Hosman & van der Vaart (1978, 1980, 1981), Decker, Adam & Gerdes (1986), Showalter & Parris (1980), and others)). In addition, there are several works which indicate the effects on control behavior of vestibular stimulation (Hosman and van der Vaart (1981), Junker and Levison (1978), Zacharias (1977)).

  The value of vestibular stimulation for training is more controversial. Gray and Fuller (1977) as well as several others have indicated virtually no transfer of training due to providing vestibular stimulation. However, Caro (1979) indicates that there is a relationship between the maneuver type, the quality of the data, the training objective and the composition of the motion being provided that affects the results of transfer of training studies. Hall (1979) presents similar views to the extent that he classifies motion into two categories: disturbance and maneuver motion and further classifies maneuver motion into categories depending on simulated aircraft handling qualities.

- Pitch sensations for pitch onset.

  The discussion for roll applies equally to pitch.

- Disorientation due to Coriolis effect.

  Because of head movements out of plane with extant motion, the coriolis illusion (Young (1982)) is often experienced. This illusion produces an unpleasant sensation and may lead to motion sickness symptoms. If the simulator pilot is experiencing vection and moves his head in an out of plane direction, the pseudo-coriolis illusion may result.

CARDIO-RESPIRATORY

- G-Dimming.

  G-dimming, also called "grayout" and, in the extreme, "blackout," is the contraction of the visual field due to the collapse of the retinal vasculature during moderate to high G exposure. This is a well known effect which has been studied extensively. Christiansen and Johnson (1958) report that pilots actually use the extent of g-dimming to regulate g-producing maneuvers (a pullup or a tight turn).

- Increased breathing effort and breathing difficulty.

  G-loading of the torso tends to compress the lungs and increases the effort required to breathe and to speak. This effect has been studied extensively. See, for example, Leverett and Whinnery (1985) and Christiansen and Johnson (1958). While the cited references document the physiological effects, no evidence was found to support training or performance value of these effects.

- G-suit inflation.

  G-suit inflation is readily apparent to the pilot and therefore a part of the sensory environment of high-G maneuvers. Two USAF fighter pilots interviewed by the authors in studying the pop-up maneuver both indicated that g-suit inflation is a significant sensation during accelerated maneuvers.

SOMATOSENSORY

- Small bodily accelerations.

  Experiments have indicated beneficial effects on performance in a simulator due to somatosensory stimulation to simulate small bodily accelerations (McMillan et al. (1985), Martin et al. (1987), and McKissick et al. (1983)).

- Bomb "unloading."

  Aircraft configuration changes result in small accelerations coupled to changes in aircraft performance. Pilots are quite sensitive to these changes and generally interpret them accurately. Bomb release causes a sudden, small decrease in aircraft weight and drag and thus a sudden acceleration, ballooning and change in elevator control pressure. The pilots interviewed for this study indicated that "bomb unloading" was the pilot's verification that release had actually occurred and that the pullup could begin. Expected configuration changes add realism, however, they should not be expected to change performance on specific tasks.

- Vibration.

  Vibration provides information about the vehicle state such as impending stall. Vibration also increases workload by making tasks more difficult to perform. In addition, the conventional wisdom is that vibration may mask vehicle maneuver accelerations. However, in a study by Clark et al. (1980) it was found that rotary vibratory motion has little or no masking effects on the detection of constant angular acceleration over a wide range of constant angular acceleration levels. Hence, one should not expect to mask motion washout with vibrations. However, this experiment does not fully address the issue of detection in an increased workload environment since the subjects were not required to control the vehicle in this experiment.

  It is also well known that vibration can degrade visual acuity (Barnes, Benson & Prior (1978)).

- Head heaviness.

  Apparent head weight is increased in direct proportion to G_z, i.e. if G_z increases by a factor of three, head weight does as well. Kron, Cardullo and Young (1980) report experiments performed by Kroemer and Kennedy that the eye point was depressed 50 mm under G_z of which 83% was due to increased head/helmet weight and the remainder due to head pitch.

  The results of experiments conducted at NASA Langley Research Center illustrate a beneficial effect of head loading on performance in a simulator (Ashworth and McKissick (1978)).

- Limb heaviness.

  Limb weight rises in direct proportion to G_z in the same

manner as head weight. The increase in limb weight significantly impairs movement in the cockpit. For instance, at $+3G_z$ it is nearly impossible to raise the leg, at $+8G_z$ the forearm can't be raised above the armrest (Kron, Cardullo and Young (1980)). The literature is replete with the physiological effects of limb heaviness. The importance of exploiting it as a cuing modality is based on conjecture or anecdote. Much has also been written about the muscular response to increased limb weight (Borah (1977)).

- Seat pressure.

  Increase in seat pressure, due to G_z, is reported frequently in the literature (Kron et al. (1980), Christiansen and Johnson (1958)), can be shown on the basis of the physics involved, and is frequently reported by pilots. The value of sensible seat pressure to simulator effectiveness is presented in Showalter and Parris (1980). These authors show improved performance in a simulator, due to control of buttocks pressure, for three piloting tasks. Showalter (1978) reports on the effects of differences in g-seat drive algorithms on pilot performance.

- Mask sag.

  Mask sag is another case where the physical and physiological effects are well known, but the usefulness of mask sag as a cue is not well researched. Evidence of mask slippage is presented in Leverett and Burton (1976). It could be concluded that if the mask sags it will stimulate the sensitive somatic sensors in the face, thereby producing a significant cue. Indeed, Christiansen and Johnson (1958) acknowledge that mask sag is a cue, but it ranks near the bottom of the list of reported pilot sensations due to $+G_z$.

- Back scrubbing.

  Back scrubbing is similar to mask sag in that the physiological argument for the existence of the cue is readily appreciated. It follows that as the posture of the pilot in the cockpit is altered by the body's inertial reaction to aircraft acceleration, the tactile receptors in the back will sense the movement. One then speculates that this would be a useful cue. This speculation is partially based on individual experiences of postural changes while negotiating a sharp curve in an automobile. However, except for some anecdotal evidence, there are no experimental data that back scrubbing has any effect on behavior or performance. There is no evidence that it has any training value.

- Postural response to roll.

  The vestibular system functions to inertially stabilize the head and eyes, when the aircraft rolls into a turn. The pilot maintains a head erect posture for a few seconds until the turn is well developed and the vestibular system adapts to the new orientation. In addition to the vestibular response, the inertia of the pilot's body tends to resist the applied roll moment, so that the seat generates forces against the buttocks and back. The postural control reflexes react to shifting support by appropriate muscular counterforces. However, there is no documented evidence of training value or performance due to this effect.

- Head and upper body side loading requires bracing.

  In the extreme case of the body's inertia resisting the acceleration of the aircraft, the pilot must brace himself to maintain the desired position in the seat. This action precludes the use of muscles for other purposeful tasks. No evidence of any training or performance effects was uncovered in the literature.

- Control Force Feedback.

  Control force feedback is well known to provide pilots with significant information about the aerodynamic state of the aircraft's lifting and control surfaces. Pilots use control force as a specific overt cue when adjusting trim and when flying at critically high angles of attack; indeed "stick shakers" are provided in many aircraft to artificially reinforce the control force sensations associated with aerodynamic buffet at high angles of attack. In less extreme flight regimes, much of the "feel" of the aircraft is derived from the perception of stick forces. In these regimes, stick force assists the pilot in modulating control inputs, avoiding overcontrolling, and detecting thresholds of control effectiveness.

  In spite of its usefulness, control force feedback is clearly not essential to pilot control. Some fly-by-wire aircraft such as the F-16 fighter and the A-320 provide no stick force to the pilot, yet these aircraft display no obvious handling problems as a result. It is interesting to note that the F-16 uses a "force stick" so the pilot feels considerable resistance to control inputs, while the A-320 uses a "displacement stick" which is inertially loaded and viscously damped in such a way that it, too, provides sensible resistance to pilot inputs.

AUDITORY

o Engine and slipstream sounds.

Engine and slipstream sounds are certainly evident to the pilot and are, therefore, part of the sensory environment of the maneuver studied. The auditory pitch and intensity of slipstream and engine sounds are quite sensitive to airspeed and are, therefore, indicative of pitch attitude changes. Pilots use this auditory cue to detect disturbances in pitch attitude. All evidence of training or performance value of these cues is anecdotal.

3.5.5 Frequency Domain Analysis of the Cues

In a complete analysis of a maneuver, all stimuli shown by the task analysis to be important for pilot performance or training would be submitted to frequency domain characterization. For purposes of this example, however, only the vertical acceleration (G_z) cues will be evaluated. The time history of G_z, f(t), as derived through task analysis, is shown in Figure 3.5-4. The vertical acceleration spectrum, F(ω), is given in Figure 3.5 5. This curve was computed as a discrete Fourier transform of f(t). Notice that F(ω) follows the general form described above. Since the task analysis treats only one execution of the maneuver, not the sum of many repetitions, each slightly different, the structure characteristic of the specific maneuver has not been washed out. Further, the analysis does not take into account any disturbance motion. Since disturbances generally occur at

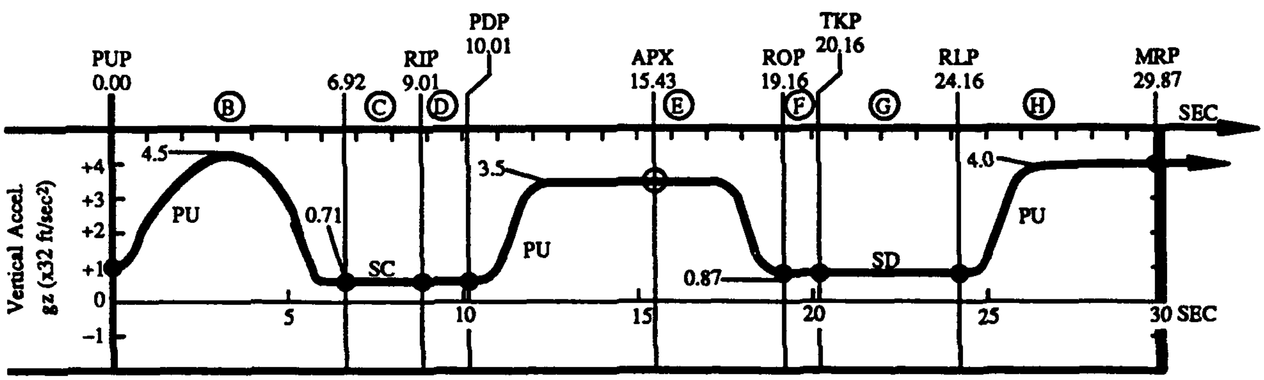

Figure 3.5-4. The time history, f(t), for the vertical acceleration of the pop-up ground attack maneuver as executed in the F-4 aircraft.

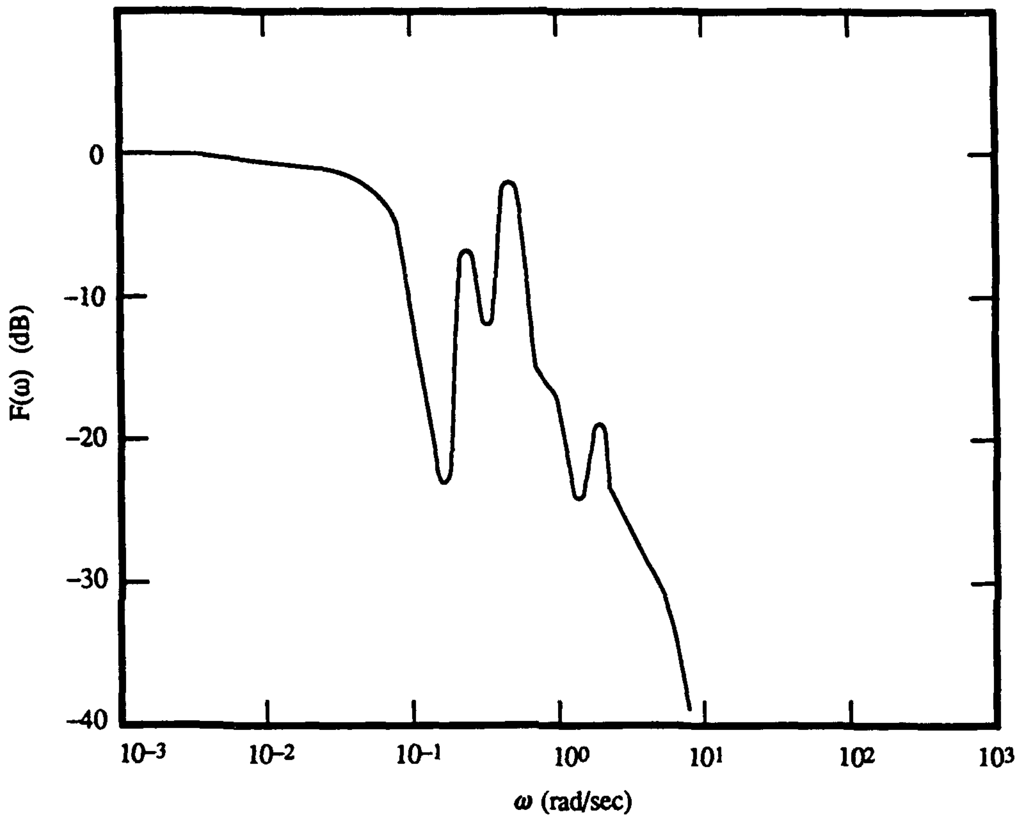

Figure 3.5-5. Vertical acceleration spectrum, $F(\omega)$, of the pop-up ground attack maneuver as executed in the F-4 aircraft.

frequencies above the characteristic frequencies of the maneuver components of the pop-up, inclusion of disturbance motion would raise the cutoff frequency slightly. G-forces associated with disturbance motion are relatively small compared to the operational g-forces in this example, but in other operations, disturbance motion may predominate.

Vertical acceleration is cued in many simulators with a motion platform, the primary function of which is to stimulate the otoliths. The transfer function, $T(\omega)$, for the otoliths is given in Figure 3.3-2. The real-world spectrum of the otolith output signal is $A(\omega)=T(\omega)F(\omega)$ as shown by the upper solid curve in Figure 3.5-7.

In the simulator, the otolith sensory channel includes the filtering action of the motion platform. A high-performance motion platform would behave like a slightly underdamped, second order system with a cutoff frequency of about 3 Hz (19 rad/sec). At high frequencies, as the frequency increases, the excursion produced by a constant amplitude acceleration input decreases. At low frequencies, however, the excursion amplitude increases with frequency and will exceed the capacity of the platform if not attenuated. Thus, in the high frequency regime, the motion system acceleration frequency response is just the same as its displacement frequency response; but at low frequencies, because of the limited excursion of the platform, its acceleration response must be attenuated by the cuing algorithm at a rate of ω^2/ω_L^2. Here, ω_L is the low frequency cutoff, and is given by the ratio of maximum displacement to maximum acceleration: ω_L^2=Amax/Zmax.

For the example, suppose that the maximum excursion amplitude is 3 feet and the maximum acceleration capability is 0.5G. In the pop-up example, the onsets of pulls as large as 3G are to be cued, so the cues must be scaled by $K_0=1/6$. The low frequency cutoff will be at 0.4 rad/sec (0.07 Hz), with amplitude rising at 40 dB/decade. The frequency response of this motion platform is shown in Figure 3.5-6. The platform obviously does not have the low frequency response to stimulate the otoliths in the same way as the real aircraft, nor the acceleration capability to create high-g stimuli at any frequency.

The otolith AFR, $S(\omega)=F(\omega)T(\omega)M(\omega)$ in the simulator, is shown as the lower, heavy solid curve in 3.5-7. Evidently, the motion platform provides somewhat attenuated cuing at the higher frequencies, but is completely inadequate at the lower frequencies.

The question now is, given that the pilot senses (and perceives) low frequency acceleration (as shown in the $A(\omega)$ plot), can we find another cuing device to fill in some more of the spectrum? The approach must be to devise a cuing device to excite a

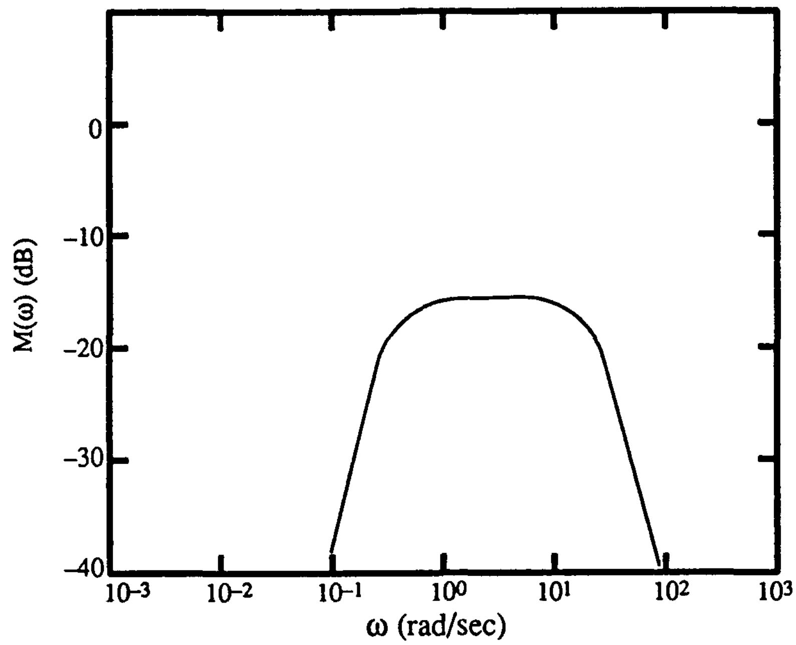

Figure 3.5-6. The transfer function, $M(\omega)$, of the heave axis of a motion platform.

different sensory channel at low frequencies; low frequency stimulation of the otoliths is probably a lost cause short of direct neural stimulation or putting the simulator cockpit on a centrifuge. A g-seat, however, is a possible candidate.

The g-seat stimulates the pressure sensors in the buttocks by varying the firmness of the seat cushion as a function of G_z. The result is that the effective seat area is reduced with increasing simulated G_z, thus increasing the compression of tissue between the ischial tuberosities and the seat pan. (The g-seat also raises and lowers the pilot thus stimulating back-scrubbing and vision, and although these are very important stimuli, we ignore them for the sake of the example.) The amount of seat area decrease is only about a factor of 1/2, so cue scaling will again be required. The transfer function for the g-seat is shown in Figure 3.5-8.

The sensory organs stimulated by buttocks pressure are primarily the Pacinian corpuscles. Their transfer function, $T(\omega)$, for pressure to AFR, is given in Figure 3.3-2. The afferent firing rate due to aircraft acceleration is $A(\omega)=T(\omega)F(\omega)$, shown as the upper solid curve in Figure 3.5-9.

In the simulator, the commanded acceleration, $F(\omega)$, acts on the pilot through the g-seat dynamics rather than the aircraft seat dynamics. In the aircraft, the seat transfer function is simply the constant ratio of pilot mass to seat area, m/a, but in the g-

seat, the applied acceleration is always $G_z=1$ (at low frequencies, anyway), and $F(\omega)$ acts on seat area. Typical operational g-seats display a single-pole low pass characteristic with a cutoff of about $\omega_N=0.75$ Hz (4.7 rad/sec) and a dc gain given by the amount that the seat area can be reduced. If the seat area can be reduced by a factor of about 1/2, then the maximum pressure which can be exerted is that equivalent to 2G (a 1G increase). For the pop-up mission, maximum acceleration is about 3G, so the gain of the seat is $K_0=1/3$, or -9.5dB. The frequency response of the hypothetical g-seat, $M(\omega)$, is shown in Figure 3.5-8.

The final sensory output is $S(\omega)=F(\omega)T(\omega)M(\omega)$ in the simulator, and is shown as the lower, heavy solid curve in Figure 3.5-9. In terms of frequency response, the g-seat is quite faithful to the real world--its cues are simply weaker by 9.5 dB, as expected.

The purpose of adding a g-seat to the hypothetical simulator design was to extend the bandwidth of vertical acceleration perception to lower frequencies. Figure 3.5-10 presents a summary of the motion platform and g-seat sensory outputs, together with the real world otolith and pressure receptor channels. The g-seat extends the cuing bandwidth down to about 0.05 rad/sec (0.08 Hz, or about a dozen seconds of steady G_z cuing), although the cues are still some 10 dB weaker than those received in the real world through the tactile sensory channel. Tactile stimulation by the g-seat is clearly not a satisfactory answer to the problem of low frequency g-cuing, however. Although the g-seat itself has a strong low-frequency capability, the Pacinian corpuscles are subject to adaptation and therefore cannot take full advantage of very low frequency stimuli. G-seats, however, not only stimulate buttocks pressure, but back scrubbing and visual effects as well. The visual effect of the pilot sinking down in his seat under g-loading is a prominent low frequency acceleration cue provided by the g-seat (see Showalter (1978)). Further analysis could be used to quantify this effect.

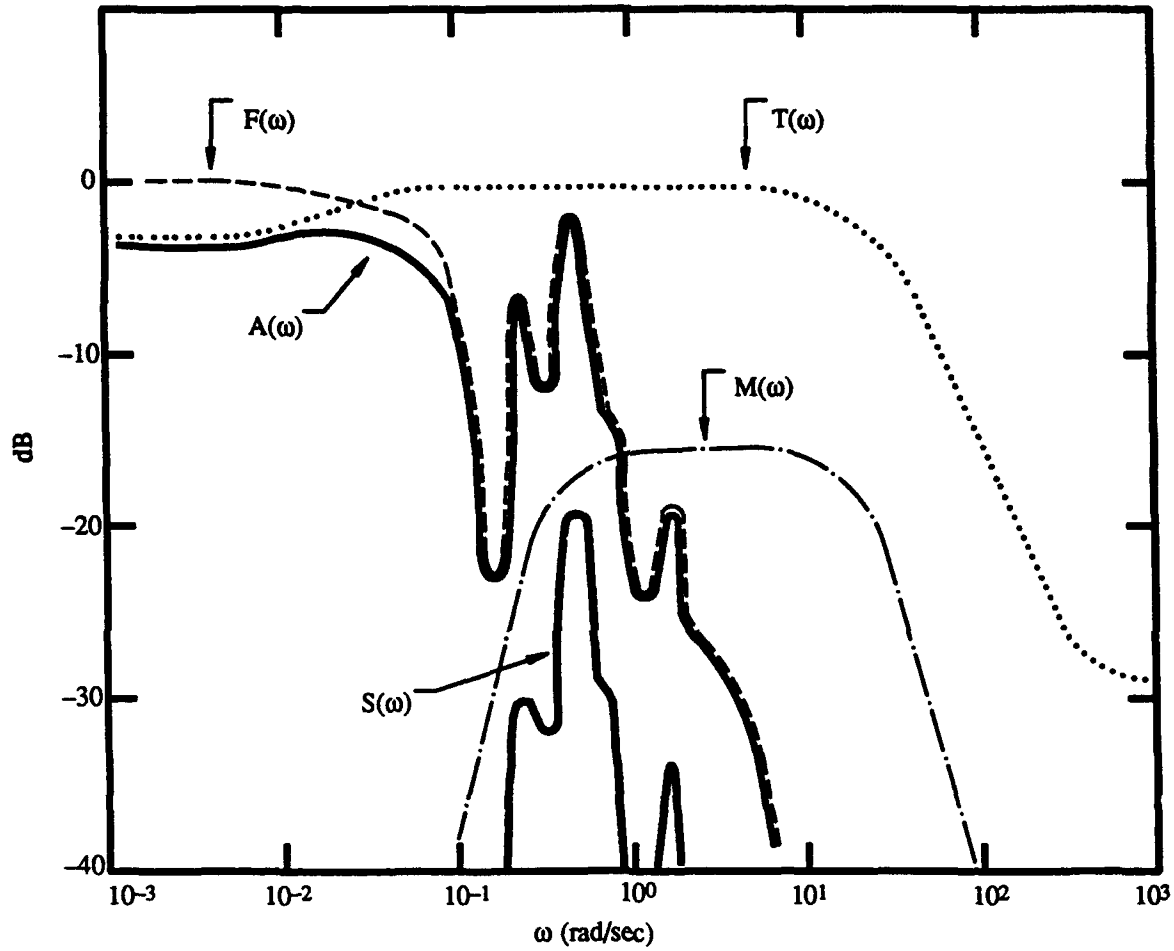

Figure 3.5-7. Summary of the analysis of the otolith sensory channel. F(ω) is the aircraft vertical motion spectrum, T(ω) is the otolith transfer function, and A(ω) is the resulting sensed aircraft motion spectrum. M(ω) is the vertical transfer function of the motion platform, and S(ω) is the resulting sensed motion spectrum in the simulator. Note that S(ω) lacks the low frequency components present in the aircraft spectrum, A(ω).

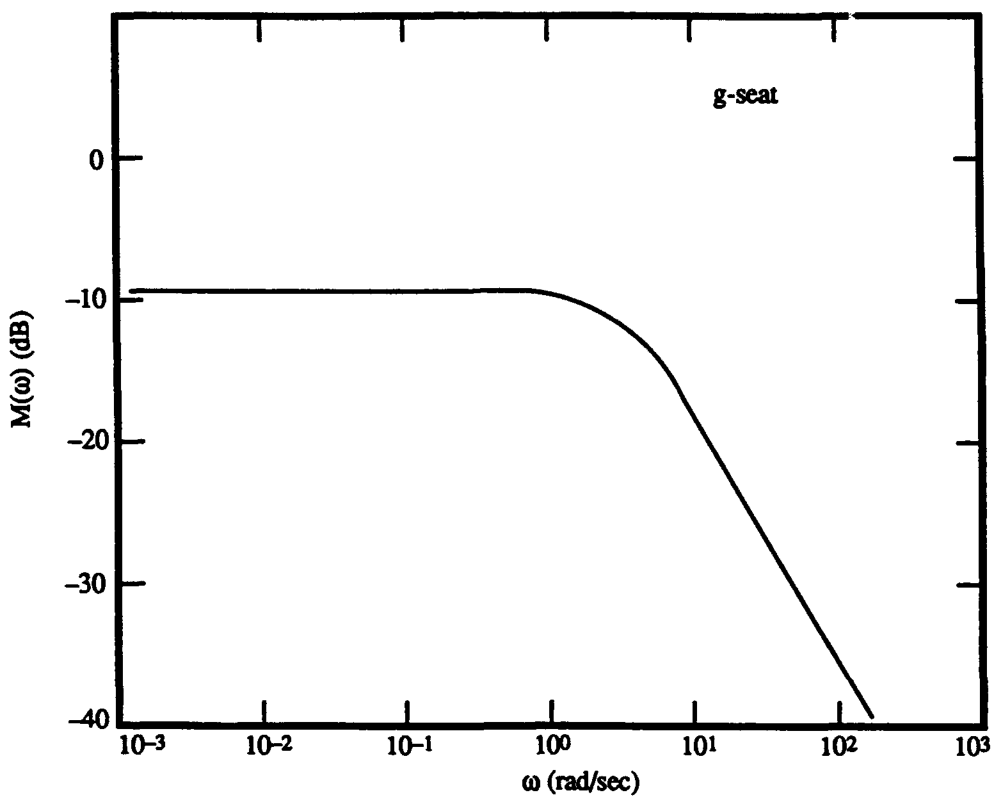

Figure 3.5-8. The transfer function, M(ω), for the seat pressure cue of a g-seat.

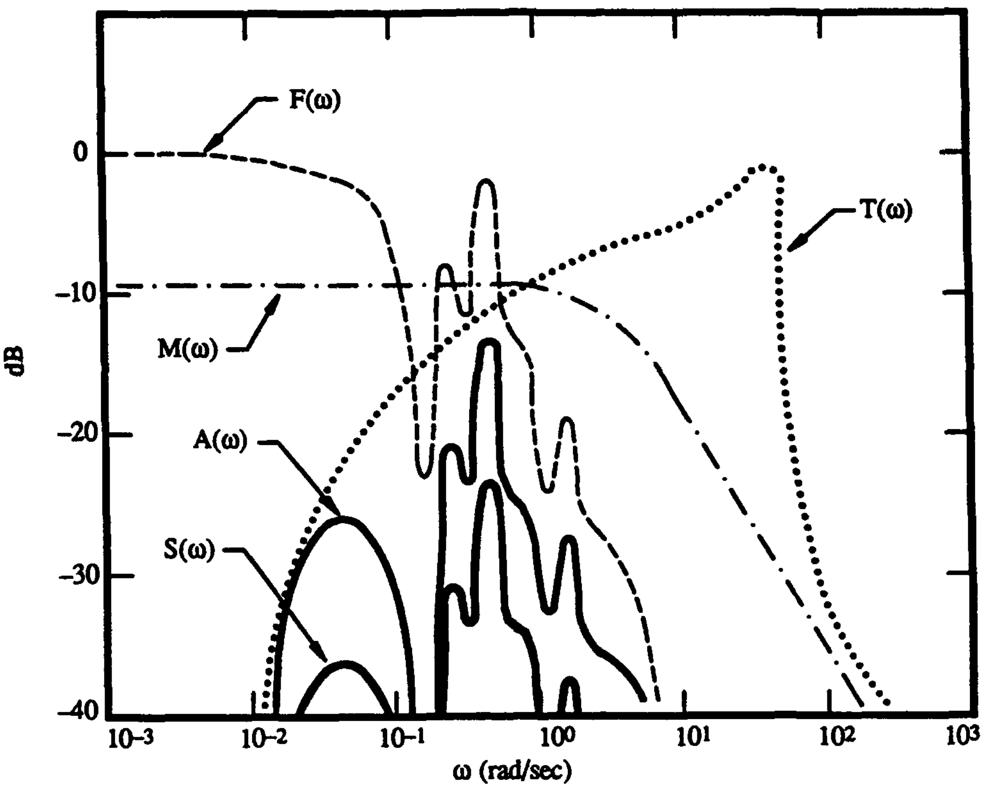

Figure 3.5-9. Summary of the analysis of the tactile sensory channel. $F(\omega)$ is the aircraft vertical motion spectrum, $T(\omega)$ is the Pacinian corpuscles transfer function, and $A(\omega)$ is the resulting sensed aircraft motion spectrum. $M(\omega)$ is the vertical motion cuing transfer function of the g-seat, and $S(\omega)$ is the resulting sensed motion spectrum in the simulator. Note that, in this case, $S(\omega)$ includes more low frequency components than $S(\omega)$ for the motion platform.

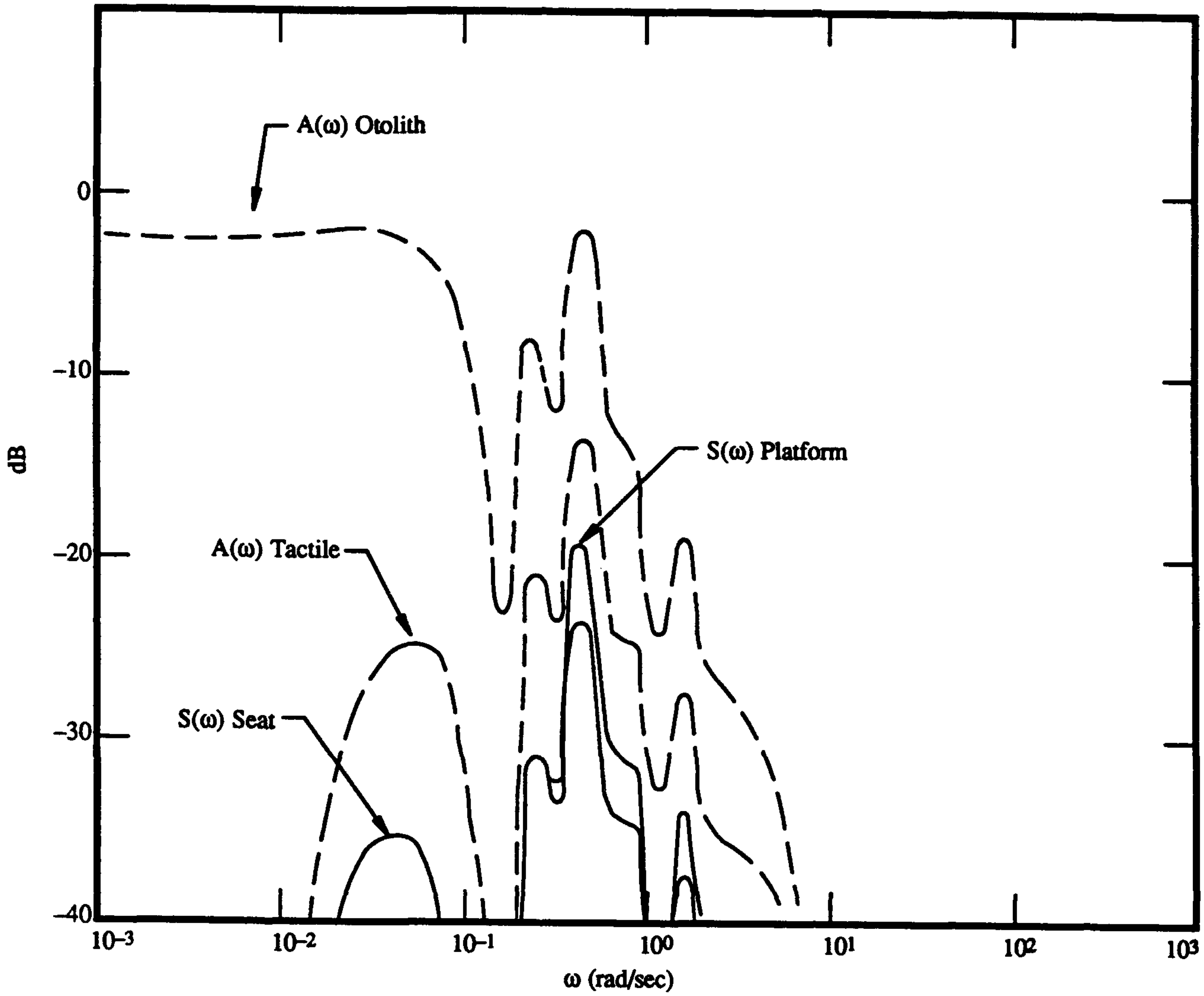

Figure 3.5-10 Summary diagram showing the two channels of Gz sensation studied. A(ω) indicates the sensed motion spectrum in the aircraft, while S(ω) indicates the sensed motion spectrum in the simulator.

4.0 Some Possible New Cuing Techniques

4.1 Optimization of Existing Devices

4.1.1 The Advanced Dynamic Seat

The early generation dynamic seats were designed to provide sustained acceleration cues complementary to the onset cues of a platform motion system. As such, these devices had low bandwidth, less than one Hertz, and were driven in a corresponding fashion by their cuing algorithms.

In order to optimize dynamic seats, two approaches may be employed. Improvements may be made to both the hardware and software. The main improvement in hardware is to provide a bandwidth of at least four Hertz. This bandwidth is necessary to minimize the equivalent delay resulting from phase shift. A bandwidth of 10 Hz has been achieved with a hydraulic dynamic seat (Kleinwaks (1980)). However, it would be desirable to achieve the four Hertz with a pneumatic seat to minimize initial cost and maintenance. Since most rigid body dynamics of an aircraft lie below one Hertz, the transport delay criterion is the motivating factor for the bandwidth requirement.

The other major improvement which can be made in the dynamic seat is the cuing algorithm. As stated previously, cuing algorithms in the past have been designed to drive low bandwidth seats in a sustained cuing mode. Some research into dynamic seat cuing algorithms has been conducted. Showalter and Cook (1978) investigated mainly the directionality of the cues for three piloting tasks. The majority of the work in this area has been conducted at the Armstrong Aerospace Medical Research Laboratory (AAMRL), Wright-Patterson Air Force Base. McMillan et al. (1985) investigated two major aspects of the cuing algorithm, the independent variable and the gain. These researchers considered algorithms where seat position was proportional to simulated aircraft acceleration, velocity and position with various constants of proportionality. Of the three approaches, the velocity algorithm yielded the best pilot performance. Subsequently, a so-called sigma algorithm, which combined velocity and position, was implemented and yielded even better results (Flach, et al. 1986). These AAMRL experiments were conducted on the roll, and pitch axes (Cress, et al. 1989), and with very narrow field-of-view symbolic displays.

These experiments are being repeated with a wide field-of-view, out-the-window display and extended to maneuvers in the linear degrees of freedom. Based on the vection experiments of Young, et al. (1975 and 1977), this should be productive research since they showed significant reduction in the latency of vection (visually induced experience of motion) in the presence of very small vestibular stimulation in the appropriate direction.

4.1.2 Motion Platforms

Much of the discussion of dynamic seats is also applicable to motion platforms. Most commercially available motion platforms have bandwidths of less than three hertz with the sizeable payloads as are encountered with large field-of-view visual systems. A bandwidth of four Hertz is required to minimize the transport delay. To achieve this bandwidth, some different approaches in motion platform control systems design are required. Servo design which accounts for changes in reflected mass are necessary. One approach to satisfy that requirement would be to implement an acceleration servo with some sophisticated compensation technique.

Another related hardware problem is that in most commercially available motion systems, the hydraulic column resonant frequency is at or below the desired bandwidth. This often doesn't appear to be the case when the system is analyzed with the platform at the neutral point and the load equally distributed among all six actuators. However, when the platform is driven away from neutral and the resulting geometric and inertial effects are considered, the reflected mass at each actuator changes substantially, consequently altering the resonant frequency of the hydraulic column. This phenomenon results in bandwidth reduction as a function of the extant dynamics. The control system design suggested previously would address the varying reflected mass as it affects bandwidth, however, the hydraulic system should be designed with sufficient stiffness to yield a sufficiently high resonant frequency for all conditions of reflected mass. Notch filter techniques may also be employed to allow the bandwidth to exceed the resonant frequency. However, the notch bandwidth must be adaptable to the extant dynamics. A potential problem with the notching approach is that it might result in spurious motion resulting from crosscoupling effects.

The issue of spurious motion is another contaminant of motion cuing. Most testing for this effect is done close to the motion system neutral point in the absence of the drive software. However, the problem exists mainly away from the neutral point. This problem largely arises from the fact that the human perceives motion and the cuing algorithm computes simulator motion in degree of freedom space, while the motion system servo control is performed in leg space. It would be worth studying the feasibility of designing future motion systems with servo control performed in degree of freedom space. The advent of digital motion servo control systems facilitates this endeavor.

The impact of spurious motion is that it might destroy extant vection or cause the pilot to react to a motion stimulus which is an artifact of the simulation. Such artifacts reduce the effectiveness of the simulator. Because of this undesirable artifact, the tendency is to minimize the gain on cues, thereby,

constraining the platform to motion very close to the neutral point.

The software cuing algorithms have not kept pace with the hardware development. The most acceptable currently available, cuing algorithm is that which was developed at NASA Langley in the early seventies by Parrish et al (1973). However, other than some research efforts; Busolari and Young (1989), Ried (1987), Hosman and van der Vaart (1979), Cardullo and Kosut (1979, 1983), not much has been done to improve motion cuing algorithms. A worthwhile effort would be to evaluate these experimental techniques and develop a cuing algorithm which incorporates the best features of each. All of these are perceptually based, and are adaptive and nonlinear to some degree. In the past, most algorithms were linear, with perhaps some quasi-linear effects superimposed on the basic linear cue.

4.1.3 Visual Systems

Visual systems certainly provide strong motion stimuli, particularly at the low end of the frequency spectrum, <.06 Hz (Huang & Young (1988)). The visually-induced perception of self motion is the well known vection illusion. While it is likely that vection is induced for motion through the visual scene, it seems, based on the dynamics of vection as reported by Young (1977), unlikely that much circular vection due to simulated aircraft rotational maneuvers actually occurs in a flight simulator.

It would be useful to attempt to measure vection in a simulator to ascertain which, if any, maneuvers stimulate the illusion. Also, it would be important to discriminate between the effects on performance of ego motion versus motion of the scene. Either way, this would have a significant impact on the design of motion cuing devices.

4.2 New Developments

4.2.1 Lower Body Negative Pressure

One of the more profound physiologic effects of $+G_z$ acceleration is the reduction of head-level blood pressure due to pooling of blood in the pilot's lower extremities and due to the increase in pumping energy required to raise blood against its increased apparent weight. Although to some extent the cardiovascular regulatory system can compensate for acceleration stress, the body's reaction time is slow compared to aircraft acceleration onset times, and it is effective only up to a few Gs. The most obvious consequence of the reduction of head-level blood pressure is the "G-dimming" or "acceleration blackout" phenomenon in which collapse of the retinal vasculature results in a progressive narrowing of the pilot's field of view. Prolonged exposure to

low head-level blood pressure eventually results in g-induced loss of consciousness (GLOC).

A number of pilot protection methods have been devised to increase pilot tolerance to G_z. The anti-G suit prevents or reduces pooling of blood in the legs and abdomen by applying pressure to those regions while the pilot is exposed to high accelerations. The M-1 and L-1 straining maneuvers help to reduce pooling of blood in the lower body through the contraction of skeletal muscles. They raise head-level blood pressure through compression of the pericardium and lung cavity. In the simulator environment, however, sustained acceleration cannot be produced, so the dramatic and important G-dimming cue is not provided, straining maneuvers are dangerous, and the operation of the g-suit is inappropriate. While it gives a useful cue, it is physiologically inconsistent. Consequently, current simulators provide highly inadequate simulation of the acceleration environment of a tactical aircraft.

Although sustained acceleration is impossible to provide in a simulator, it is possible that the physiological effect of pooling blood in the lower body may be stimulated through the reduction of atmospheric pressure over the lower body. In terms of its cardiovascular effects, at least, Lower Body Negative Pressure (LBNP) has been suggested as an analog for vertical acceleration. LBNP has been studied for various medical reasons since the mid-nineteenth century, and since the 1960s, has served as an analog for terrestrial gravity in preventing the cardiovascular deconditioning experienced by astronauts exposed to microgravity for long periods. That LBNP could serve as an analog for aircraft acceleration in a flight simulator was first proposed by Howard (1976), and various investigators (eg, Lategola and Trent (1979)) have explored the idea since. Nevertheless, no truly comprehensive study has been attempted which would establish an effective method of using LBNP to si~ulate aircraft accelerations.

In spite of the appealing parallels between the abilities of LBNP and G_z exposure to produce pooling of blood in the lower extremities, and to produce unconsciousness, their physiologic mechanisms are not entirely similar. Vertical acceleration acts on the cardiovascular system mainly by increasing the amount of work the heart must do to raise blood out of the lower body against its increased apparent weight. LBNP acts by merely expanding the compliant venous vasculature of the lower extremities. Although there is considerable anecdotal evidence that pilots experience similar sensations when exposed to LBNP and when exposed to G_z, there is no data supporting any quantitative correlation between LBNP and G_z in terms of levels of exposure or onset rates. Krock (1989) argues that no similarity should even be expected (except, perhaps, by matching

very slow G_z onset to very rapid LBNP onset), and is currently performing experiments to test his assertions.

Since acceleration exposure is such an important part of the tactical pilot's working environment, awareness of its effects and training in protective measures are vital both to the safety of the pilot and to his mission effectiveness. Although LBNP does not appear today as promising as it once did, it still deserves attention as an element in G_z training devices and in air combat simulators. Appendix B describes an approach to investigating the use of LBNP and Upper Body Positive Pressure (UBPP) both as a cuing device for tactical aircraft simulators, and as a physical conditioning device for acceleration awareness and pilot protection training.

4.2.2 Artificial Somatosensory Stimulus

The purpose of most of the components of a flight simulator is to provide accurate and faithful reproduction of the physiological cues a pilot experiences in actual flight. The goal of the simulation engineer is to develop ways of improving the accuracy and faithfulness of the cues provided. The somatic cues associated with sustained acceleration are particularly difficult to present in a faithful way, however, and it may therefore be necessary to modify somewhat the goal of physiological fidelity. A faithful reproduction of acceleration induced forces and body pressures is difficult because any simulation-appropriate applied force or pressure must be balanced by a simulation-inappropriate force in the opposite direction. For example, the force on a pilot's seat is always equal to his weight. In the aircraft, under acceleration, this force increases proportionally to the z component of acceleration--and the sensation of "seat-of-the-pants" pressure is thus an important acceleration cue. In the simulator, where there is no actual acceleration (ignoring onset cues from a motion system), the force on the pilot's seat is constant and equal to his weight. There is no physically possible way of increasing this force except by pushing down on the pilot; pushing up on the seat is impossible without displacing the pilot upwards.

The pilot's perception of his weight on the tissue of his buttocks is due to compressive stress, however, not force. So the simulation engineer has the opportunity to provide an increase in stress as an acceleration cue. The G-seat cues acceleration by reducing the area of contact of the pilot's buttocks with the seat pan thereby increasing the actual stress applied to a localized region (the tissue padding the ischial tuberosities). This action is not a completely faithful simulation of the effects of acceleration, but it does provide some appropriate cuing through natural stimulation of the same physiological receptors as are active in the real world.

Given the difficulty of actually applying forces similar to those encountered in the real world, it is reasonable to ask if other means of stimulating the involved physiological sensors--or of amplifying the effects of available stimuli--are practical. A simple elaboration of the G-seat concept might be to fit the simulator seat with an array of dowels which could be pushed up through the seat cushion to apply high localized pressure to the pilot's buttocks in response to simulated acceleration. The sensation would not be entirely realistic, but it would provide a dramatic--and physiologically relevant--acceleration cue.

A willingness to depart from a requirement for absolute realism opens even more avenues for useful cuing. There is some evidence, both experiential and physiological, that the mechanisms of pressure sensation and temperature sensation are related (Inman and Peruzzi (1961); Loewenstein (1971); Mueller (1965); Zotterman (1976)). It is possible, therefore, that the pressure cue of a G-seat could be enhanced or amplified by the simultaneous application of a temperature change to the pilot's seat. The pilot would not, of course, confuse a temperature change with a pressure change, but the thermal effect may enhance the existing pressure cues, and, realistic or not, may serve as a suitable analog for sustained g-induced seat pressure. A thermal cutaneous stimulator employing inexpensive Peltier Effect heat pumps would be remarkably simple to implement if the technique was to prove effective. Appendix C discusses the engineering considerations involved in developing such a device. Another possibility is to substitute a shear stress for the compression stress associated with vertical acceleration. Again, such a cue is not physically faithful to the real world effect, but it can be made very dramatic, and does stimulate the relevant physiologic sensors. Shear strain can be applied to the tissues of the pilot's buttocks by fitting the seat pan with two rotatable plates, one under each ischial tuberosity, and using them to apply a twist to the skin above them. Another approach would be to provide two plates (or rollers) in the seat pan which push the skin over each tuberosity towards the sagittal plane.

A final possibility, suggested by Dr Larry Young in a conversation, is to fit the seat with an array of vibrating points. The vibration would stimulate the pressure receptors in a way which Young speculates may actually be perceptually faithful. There are obvious safety and pilot acceptance issues associated with this "bed of nails" concept, but the approach nevertheless deserves attention.

4.2.3 Limb, Head and Equipment Loading

Although the forces associated with pilot g-loading cannot be applied in a stationary environment without inappropriate counter forces, the constraints on action produced by limb, head and equipment g-loading is a major component of g-stress. It seems

reasonable that direct application of these kinds of forces would enhance the effectiveness of a high-g simulation. The use of electric or pneumatic actuators for applying forces to the pilot has been explored with some success in the past (Ashworth and McKissick (1978)) and deserves further attention. Appendix D discusses the use of electric torque motors to provide simulated g-loading to a pilot's forearm.

The use of a mechanical head loader to simulate the lateral forces on a pilot's head provides an instructive example of the frequency domain analysis technique described in Section 3. In the F-4, the pilot's head is located about three feet above the roll axis of the airplane, so that during roll onset and offset angular acceleration applies a lateral force to the pilot's head. A simple arrangement of torque motors and cables attached to the helmet can certainly provide forces of the appropriate magnitude.

The pilot counters the experienced force by contracting the appropriate muscles of the neck and upper body. Much of the sensation of the force is due to the nervous system activity associated with maintaining posture while the force is present. Section 3.1.2 discussed the Golgi tendon model for the reaction of the neck muscles to an applied acceleration in the y (lateral) direction. This model is appropriate to characterize the pilot's sensory reaction to head loading during roll onset and offset. The frequency response of the head/neck sensory system, $T(\omega)$, is shown as the dotted line in Figure 4.2.3-1. The curve shown is for the condition of vertical acceleration of approximately 0.8g, since the two roll maneuvers of the pop-up occur under slightly unloaded conditions due to the pitch of the aircraft.

The frequency spectrum due to aircraft motion may be derived very easily. Using the assumption that roll onset is essentially a sinusoidal pulse, and noting that the derivative of the roll rate curve shown in Figure 3.5-3, and all four associated acceleration events are essentially identical, the Fourier transform may be computed analytically. Analysis of the roll rate curve yields a critical frequency $\omega_0 = 2*\pi/0.2$ sec = 31 rad/sec for the acceleration pulse. Since the maximum roll rate achieved is 110 deg/sec, the amplitude of the acceleration pulse is 0.61 rad/sec^2. The Fourier transform of these pulses is flat up to just less than ω_0, and then drops off extremely rapidly. It passes -6 dB at ω_0 and actually touches zero at $2\omega_0$. There are fringes out beyond $2\omega_0$, but these are all more than 30 dB down below the maximum. The roll onset spectrum, $F(\omega)$, is shown as the dashed line in Figure 4.2.3-1.

The pilot's head, being about three feet off the roll axis, experiences a lateral acceleration due to roll acceleration of about 0.06g. Since a helmeted head weighs about 10 pounds, a lateral helmet loader need only provide 0.6 pounds force to simulate the lateral loads generated in the pop-up. This force

level is significant to simulation, but well within the capabilities of technology, and poses no significant safety risk. Consequently, lateral head loading is practical without cue scaling. A typical motor and cuing algorithm will have a single-pole low pass characteristic with a cutoff frequency of about 2 Hz or 13 rad/sec. The response spectrum, $M(\omega)$, is shown as the dash-dot line in Figure 4.2.3-1.

The sensory response spectrum in the aircraft, $A(\omega)$, is shown by the thin solid line of Figure 4.2.3-1; the simulated sensory response spectrum, $S(\omega)$, is the heavy solid line. The simulator shows only a minor deficit in the region of the peak of the sensory response curve--a deficit which could be eliminated by selecting a motor with slightly broader bandwidth.

Recall that, for this maneuver, the lateral acceleration of the head is only 0.06g. This acceleration level would be imperceptible if only the vestibular system were sensing it and, hence, it is likely that a platform motion system would not provide that cue. However, it can be seen from the foregoing analysis that in the aircraft the pilot would experience on the order of 0.6 pound increase of the apparent weight of his head. Therefore, the head loader would provide the only cue of the roll acceleration in the simulator.

4.2.4 Peripheral Vision Occultation

When a pilot experiences a reduction in head-level blood pressure as a result of sustained acceleration, the retinal vasculature collapses under the intra-ocular pressure. The collapse begins in the periphery of the retina and, as the blood pressure declines, progresses inward. Regions of the retina thus deprived of nourishment become insensitive to light and the pilot experiences a progressive narrowing of his field of view known as G-dimming or blackout. Initially, the pilot loses only his peripheral vision, but as the acceleration increases, the clear field becomes smaller and ultimately the entire visual field is lost. If the eye-level blood pressure is restored, whether as a result of cardio-vascular compensation, straining, the action of a G-suit, or relaxation of the acceleration itself, the pilot's vision returns. G-dimming is a particularly vivid acceleration cue, and is one which pilots rely on for gauging their physiologic state under acceleration. It would therefore be very advantageous to provide this cue in flight simulators used in training for high-G flight.

If the approach of actually reducing the pilot's eye-level blood pressure in order to produce G-dimming is rejected, it is still possible to simulate the purely visual effect by occluding the pilot's peripheral field with an appropriately designed variable transmission visor. A variable transmission visor system would consist of three main components: the visor itself, an

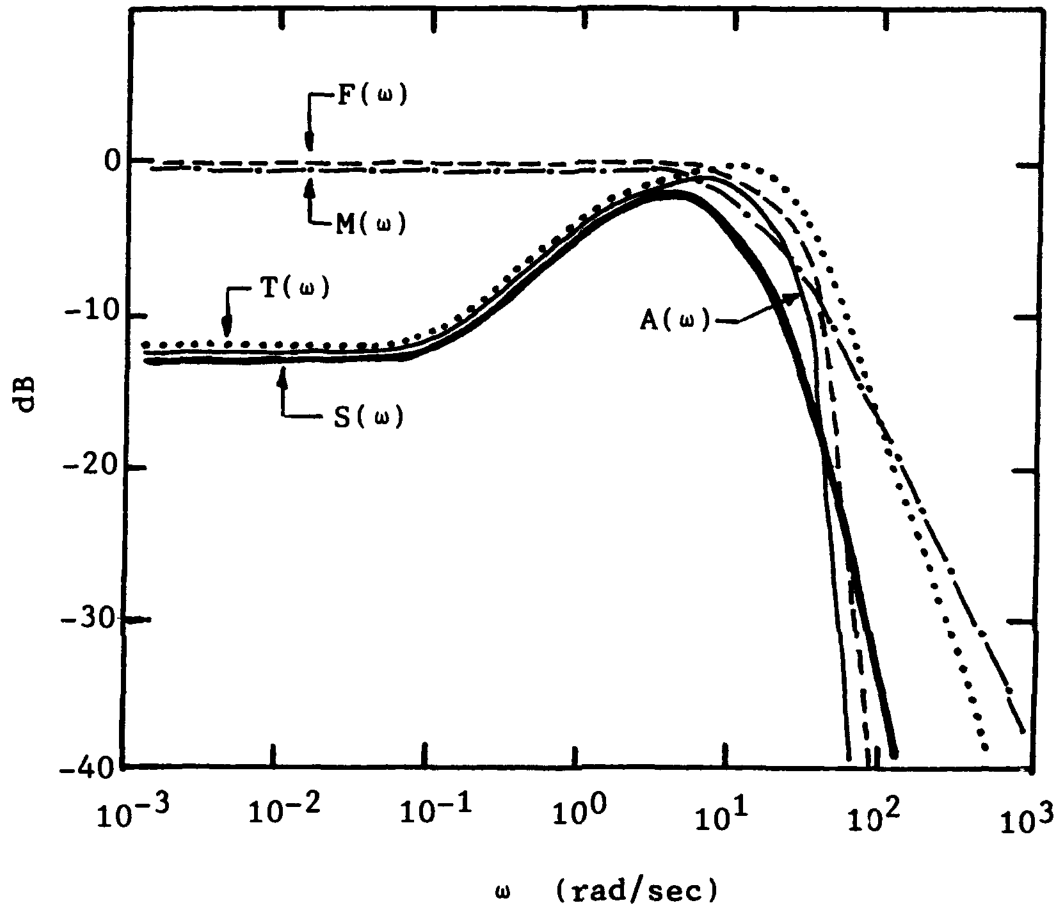

Figure 4.2.3-1. Summary of the analysis of the Golgi tendon channel stimulated by lateral acceleration due to roll onset. $F(\omega)$ is the aircraft roll acceleration (which is equivalent to the lateral acceleration of the pilot's head), and $T(\omega)$ is the Golgi tendon response at about $g_z = 0.8$. $A(\omega)$ is the resulting sensed aircraft motion spectrum. $M(\omega)$ is the transfer function of a hypothetical lateral helmet loader, and $S(\omega)$ is the resulting sensed motion spectrum in the simulator. $S(\omega)$ very closely matches $A(\omega)$, with only a minor deficit around 10 rad/sec.

oculometer for determining the instantaneous position of the eye, and a computational system for interpreting the oculometer, computing the appropriate level of G-dimming, and driving the visor. Although the visor is fixed to the pilot's head, the oculometer is required because the occulting pattern provided by the visor must be centered on the eye. The occulting mask provided by the visor must not only change size and shape as a function of blood pressure, it must track the motions of the eye. The visor, therefore, must be capable of writing an arbitrarily shaped opaque area anywhere on its surface and must be capable of rewriting its entire surface during the period of saccadic suppression--about 60 milliseconds.

Kron, Cardullo and Young (1980) have suggested that a wide aperture, transmission mode, matrix addressable liquid crystal device is a possible choice for the visor. Their exploration of this idea follows a patent by Hoyt et al. on an LCD visor which uses masks fixed on the surface, a technique which is clearly feasible but which does not allow for pilot eye movements. Although some difficulties remain, advances in LCD technology have now made possible a variable transparency visor with individual matrix addressable pixels providing full freedom in the shape and placement of the occulting mask. Appendix E discusses an approach to implementing and evaluating such a device.

4.2.5 Peripheral Vision Stimulation

Human vision contributes to the perception of the body's position and orientation in space in several complex ways, both independently and in concert with the other senses. One of the roles of the simulator visual system is to provide imagery which conveys motion and orientation information to the pilot. Much of the visual information used by pilots in this way, however, is provided not by the specific details of the scenes he sees out of the front window, but rather by the motion of textures and the position of the horizon as presented to the visual periphery. Furthermore, the pilot's visual perception of this peripheral imagery is largely subconscious; he gains from it a positive sense of his motion and orientation, but without conscious effort. The visual periphery is particularly sensitive to pure motion--apparently by mechanisms entirely different than those employed in the central field. The illusions of linear vection and circular vection may be induced by purely visual stimuli with no denotative content (although vestibular stimulation both hastens the onset and amplifies the magnitude of the effects).

Pilots make significant use of peripheral visual cues in aircraft control and tactical decision making. Studies by Malcolm, Money and Anderson (1975), indicate that the visual horizon is perceived subconsciously by pilots and used in both pitch and roll attitude control. Even when the horizon is not visible

anywhere in the field of view, the motions of textures in the peripheral scene provide strong attitude change cues and, when close to the ground, they provide an indication of speed and altitude. Tactical pilots who fly low level ingress missions report that the "ground rush" phenomenon is very important to them in selecting an operating altitude.

Modern simulator visual systems are very expensive, and their cost increases rapidly as field of view is increased. Much of the increase in cost, however is due to the computational equipment involved in generating representational scene detail and due to additional display equipment capable of rendering this type of imagery. In those applications where the training requirements do not justify the cost of wide-field visual systems, simulators often do not provide any peripheral vision cues to the trainee. Since peripheral vision stimulation does not need to involve detailed representational scenes, it should be possible to provide this type of cuing through relatively simple and low-cost equipment. A fruitful area of research may be to explore techniques of displaying in the simulator side windows visual patterns which move in response to aircraft attitude changes or which simulate the optical flowfield due to "ground rush." Experiments should be conducted to determine the effectiveness of these techniques and to determine the essential elements of the imagery presented. The effectiveness of a synthetic horizon display in the side windows also deserves investigation.

4.2.6 Vibromyesthetic Stimulation

The vibromyesthetic illusion has been investigated by Lackner and Levine (1979) and Lackner and Taublieb (1984). The illusion is one in which vibration of approximately 120 Hz is applied to postural muscle spindles creating an illusion of body and limb movement. Most of the experiments have been conducted in the dark and, if the subject observes the limb being stimulated the illusion is reportedly destroyed (Lackner and Taublieb 1984). Table 4.2.6-1 presents results reported by Lackner and Levine (1979) and illustrates that it was possible to evoke illusions of displacement and of continuous motion in virtually any desired direction. They also reported eliciting a mystagmus which was compensatory to the apparent motion the subject was experiencing.

It is possible that this illusion could be exploited as a motion cuing device in a flight simulator. However, to demonstrate its applicability studies must be undertaken in a flight simulator with a visual display system and some objective assessment of how behavior is affected. One research issue is the question of artifact. The authors experienced this illusion in the investigators' laboratory and found that the vibration was not noticed unless the subjects concentrated on it. While much needs to be done to validate this approach for use in a flight

simulator, it is a promising research area and could be pursued rather inexpensively.

Another interesting effect found by Lackner and Graybiel (1974) was that when the skull is vibrated at 120 Hz, the semicircular canals and possibly the otoliths are stimulated. This phenomenon may also be of some interest.

4.2.7 Direct Electrical Stimulation

A similarly speculative, but currently more highly developed area of artificial somatic stimulation, is the use of electrical stimuli to induce a sensation of motion or to cause actual contraction of muscles. Wild-eyed simulator designers have long wished to simply install BNC connectors in the backs of all pilots' heads, thereby providing the means to stimulate the brain directly without the necessity for cumbersome cuing devices. Electrical stimulation of the vestibular system, using surface electrodes, has been explored in a number of clinical and experimental studies. Application of small direct current stimuli (0.4-1 mA) reliably produces head and body tilts toward the anode, presumably via otolithic mechanisms (Tokita et al. (1987), Watanabe et al. (1987)). Application of sinusoidal alternating currents (0.1-2 mA) has been shown to modify the direction, amplitude, and frequency of normal postural sway. Such stimuli can even cause people to fall (Dzendolet (1963)). The work of Dzendolet and his colleagues is, perhaps, the most relevant for simulator applications. For example, Berthold and Dzendolet (1973) found that, by using low frequency (0.03-4 Hz) sinusoidal electrical stimulation applied bilaterally to a subject's mastoid processes, they could arouse sensations of rotational oscillations. The subjects were blindfolded, seated and wore acoustical ear plugs. Three types of stimulation were presented to the subjects in this experiment: mechanical rotation of the chair alone, electrical stimulation alone, and simultaneous mechanical and electrical stimulation. The subjects reported similar sensations with the electrical as with the mechanical stimuli. When mechanical and electrical stimuli were applied simultaneously, there was an apparent interaction manifested by a phase difference between the actual (mechanical) and perceived (mechanical plus electrical) stimuli. This study is especially interesting in that semicircular canal mechanisms appear to be involved.

Two possible implementations of this technology can be imagined: one would use the electrical stimulus alone to provide vestibular responses consistent with simulated aircraft dynamics; another would employ it in conjunction with a motion platform or a dynamic seat as a cue potentiator or to sustain cues after the platform or seat has reached its limit. It would seem, from the interaction described by Berthold and Dzendolet (1973), that the second alternative might prove to be problematic. However, more

research is required to either substantiate or refute these results, and to gain better understanding of the involved mechanisms. While the electroneural stimulation approach is quite promising, many questions remain: Can the sensations be calibrated? What voltage or current levels are appropriate? How long can the sensations be sustained? Do these artificially-produced sensations have the same effects on pilot behavior as normal sensations?

During the past decade, researchers have made dramatic progress in developing methods of electrical stimulation to be used in prosthetic devices for paraplegics. Petrofsky and coworkers (1986 & 1988) have succeeded in using electromuscular stimulation to enable some paraplegic patients to artificially control their limbs well enough to walk. Electromuscular stimulation might be applied in flight simulators as a means of constraining a pilot's limb movement in accordance with the simulated aircraft acceleration profile. In addition to ambulation, this technology has been applied to hand control in quadriplegics. Lieberson, et al. (1961) first demonstrated that electrical stimulation applied to the quadriceps muscles enabled a paraplegic patient to stand. Petrofsky, Phillips, and Heaton (1984) describe the control system they developed for walking. Much can be learned from this work in terms of controlling an electromuscular stimulator for simulator applications. According to Petrofsky (1990), the key to the implementation is finding a waveform for the stimulus which will generate sufficient force with the target muscle without injuring the subject, or producing pain. Although pain is not an issue with paraplegics, there is much controversy concerning the possibility of eliminating it in normal subjects.

MUSCLE GROUP VIBRATED	ILLUSORY BODY MOTION	APPARENT TARGET LIGHT MOTION DURING ILLUSORY BODY MOTION	AFTERILLUSION OF BODY MOTION	APPARENT TARGET LIGHT MOTION DURING AFTERILLUSION OF BODY MOTION
Achilles Tendons Bilaterally	Falling Forward, Moving Forward	With Body	Falling Backward, Moving Backward	With Body
Gastrocnemius-Soleus Bilaterally	Falling Forward, Moving Forward	With Body	Falling Backward, Moving Backward	With Body
Quadriceps Bilaterally	Falling Backward	With Body	Falling Forward	With Body
Rectus Abdominus	Extension of Torso	With Head	Flexion of Torso	With Head
Gluteal Muscles Unilaterally	Rotation of Body About its Long Axis Usually in Direction Opposite Vibrated Side	With Body	Reversal of Direction of Primary Illusion	With Body
Trapezius and Splenius Capitus and Cervicis Unilaterally	Tilt or Rotation of Head to Opposite Side	With Head	Tilt or Rotation of Head to Same Side	With Head
Trapezius and Splenius Capitus and Cervicis Bilaterally	Flexion of Head	With Head	Extension of Head	With Head
Sternocleido-Mastoid Unilaterally	Rotation or Tilt of Head to Opposite Side	With Head	Rotation or Tilt of Head to Same Side	With Head
Sternocleido-Mastoid Bilaterally	Extension of Head	With Head	Flexion of Head	With Head

Table 4.2.6-1 Character of Illusory Body Motion and Illusory Light Motion Elicited by Vibration of Skeletal Muscles in Experiments 3 (Lackner and Lavine (1979))

5.0 Conclusions and Recommendations for Future Work

The Phase I portion of the CUMOD program has largely fulfilled the three major objectives established for it. Its accomplishments must nevertheless be considered germinal and preliminary, since the established objectives were intended only as the foundation for more specific and narrowly focused research efforts. The key Phase I products, contained in this report and corresponding to the program objectives, are

- a bibliography resulting from the literature search,
- a description of an analytical technique which facilitates objective, scientifically-based evaluation of cuing devices and techniques (including an example of its application), and
- analyses of specific cuing techniques which appeared promising for high-G simulation.

Each of these products could benefit from additional refinement, but they also point clearly to the need for empirical evaluations of some of the cuing techniques studied during Phase I.

The sections below discuss both the accomplishments of Phase I and some recommendations for the future.

5.1 The Literature Search

The bibliography presented in Appendix A is the result of the literature search conducted during the study. The search was adequate to justify the work done, and was as extensive as possible within the resources of the program, but was incomplete. For example, the search turned up numerous unfollowed leads, and some references which were uncovered and entered into the bibliography have not been studied thoroughly in the context of the force and motion cuing problem. There is some significant ongoing work which deserves attention, but which was not yet published at the time the literature search was being conducted. Notable in this last category are the work of Krock (1989) on LBNP and the work of Lackner and Taublieb (1984) on vibromyesthetics. Since most of the study was devoted to the search for practical near-term technologies, more exotic and speculative prospects were often not thoroughly investigated. Similarly, although considerable effort was expended in gathering information about sensation and sensory modeling, less effort was directed at the more difficult and subtle question of perception and perceptual models. Consequently the bibliography is weak in these areas. Future work in bibliography development should, of course, primarily involve keeping up with the growing literature on the several subjects encompassed by the study. One worthwhile goal is a comprehensive annotated bibliography. Such a work

would certainly be a very useful tool both for researchers in the field and for those responsible for making research policy decisions.

5.2 The Cuing Analysis Technique

The central product of the Phase I effort was development of a unified analytic tool for discovering, exploring, and evaluating force and motion cuing techniques. This tool allows objective, quantitative study of the nature and relevance of cuing and sensory effects produced in the flight environment, and of the effectiveness of specific techniques for producing synthetic analogs of those effects. Despite the generality of the approach, during Phase I it was only possible to apply the technique to a single, rather simple, example. This example is valuable as an illustration of the technique itself, but does not specifically advance our detailed knowledge of the airborne force and motion environment.

Further application of the analysis tool to real problems will require the gathering of much more data on aircraft motion, and, ideally, the development of computer programs to perform the bulk of the computational work involved in using the tool. In its current form, the technique, although straightforward, is somewhat cumbersome to apply. It is possible that a simplified derivative of the procedure might be developed as an aid in preliminary analysis of cuing devices and device applications.

Whether the analytic technique is used in its present form or in a simplified version, there are basically three elements necessary to develop it into a truly useful tool for researchers and designers. First is the compilation of aircraft motion data gathered and classified over a wide range of missions and aircraft types. Such a database would combine information derived analytically, as was done for the pop-up example, and data derived empirically from instrumentation of operational and training aircraft.

The second element is the completion of a general taxonomy of cues similar to the specific analysis prepared for the pop-up example. This task will require a study of both pilot training doctrine and actual pilot performance and practice. First, all standard flight procedures and maneuvers must be identified and described in detail, compiling the pilot actions, cues and other effects involved in each maneuver according to the prescribed method. Then the relevance of each identified effect must be established through evaluation of existing research data or the application of relevant models of pilot behavior. This step is essential in determining just what it is that cuing devices are supposed to do.

Finally, considerably more research is required in the area of

sensory and perceptual models. This area of knowledge is currently the weakest component of the analysis process--and certainly the most difficult to address. To begin, it will be necessary to survey existing models and translate them into forms useful for cuing analysis. Ultimately, however, considerable new research, particularly in perceptual modelling, will be required for rigorous application of the analytical technique.

5.3 New Cuing Devices and Methods

Originally, Phase I was intended to feed directly into a Phase II effort involving experiments and other empirical investigations of proposed new cuing techniques. The Appendices to this report contain the proposed experimental research. These reports are not exhaustive in their coverage of promising possibilities, and are exclusively devoted to near-term, currently-practical concepts. They were intended as guidelines for bringing current technology and current understanding of psychophysiology into practical use in force and motion cuing. The Phase I effort did, however, identify some possible future candidates which deserve continuing research attention. It is not currently clear how to apply such effects as the vibromyesthetic illusion, thermal stimulation of the middle ear or electrical stimulation of the inner ear, but further scientific inquiry in these areas may well reveal the cuing strategies of the future.

Advances in technology and in understanding of the psychophysics of motion perception clearly indicate the possibility of advances in simulator motion cuing which could rival the progress made in visual systems and mathematical modeling techniques over the past two decades. Simulators need better force and motion cuing. With continued research, the simulator of the future can be equipped with devices which create a synthetic motion environment providing stimuli in the critical low-frequency regime, and which simulate the stresses and constraints on pilot action which are central to the pilot's experience of high-G maneuvering. The simulator of the future will not simply be an extrapolation of current technology, or simply an improvement in the ability to replicate the stimuli giving rise to the sensations of flight. Rather, it will involve techniques which synergistically create a synthetic motion environment, perceptually similar to the pilot's actual motion environment.

Although some of the techniques described in the study are highly speculative psychophysically, some of them appear to be practical with current technology. LBNP, for example, since it [illegible]ates such dramatic physiological effects, should be investigated specifically as a G-cuing device, and either ruled in or out as a candidate simulation technology. Thermal cutaneous cuing stimulation is similarly poorly understood and highly speculative, but it is simple, practical and inexpensive. The study uncovered no other ongoing research in this area, so it

seems reasonable that this technique should be a prime candidate for empirical study.

The currently practical technologies, such as the occulting visor or cable-coupled body loaders could be readily developed for widespread use in the near future, since it is already clear that they are appropriate cuing techniques.

As LCD and oculometer technology improves and matures, the LCD visor will become less expensive and more practical. Without a major breakthrough in LCD (or similar flat-panel display) technology, the problem of low clear-state transmittance will remain a constraint, however. Nevertheless, the cuing effectiveness potential of this concept is very high, and it clearly deserves further investigation.

The other somatosensory stimulus approaches discussed in this report also call for further investigation. Although analysis of the use of electric motors for direct limb loading indicated that overheating and weight would be a serious problem, motor magnet technology has advanced since the analysis was performed, and more study of the problem could result in the invention of force delivery mechanisms which separate the motor from the pilot without unacceptably cumbersome intervening linkages.

Finally, improvement of the g-seat appears to be an appropriate direction for future development effort. The g-seat concept has proven itself in research, but it is evident that a wider response bandwidth and more sophisticated design of the seat and back panels could provide significant improvement in the cuing effectiveness of the device. If LBNP proves inappropriate, an improved g-seat, enhanced by simple somatosensory cuing devices, may be the best option for near-term improvement of in-cockpit motion cuing devices.

APPENDIX A. Bibliography

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APPENDIX B. An Experimental Lower Body Negative Pressure Cuing Module

B.1 The Physiological Relationship Between G_z and LBNP

The most marked physiological effect of positive vertical acceleration is a reduction of cardiovascular effectiveness. Basically, the increased apparent weight of the blood makes it harder to pump it up to the head where it is necessary to the pilot for both cerebral and visual functioning. Under the force of $+G_z$, blood tends to pool in the lower extremities, distending the blood vessels there. Meanwhile, in the head, the vasculature tends to collapse under the intercellular pressure. This effect is not so pronounced in the intracranial region, since the cranium resists atmospheric pressure, but the vasculature of the retina does not benefit from this effect. On the contrary, because of the intraocular pressure, the retinal vasculature is the first to collapse under G-stress. Since the smaller vessels toward the periphery of the retina have lower blood pressure, the retinal vasculature is occluded progressively starting from the periphery and moving inwards as the eye-level blood pressure is reduced. Perceptually, the result of this mechanism is G-dimming, or G-induced tunnel vision: the unperfused and undernourished retinal periphery becomes insensitive to light. When the entire retinal vasculature has collapsed, the pilot experiences complete blackout.

A second important physiological consequence of the pooling of blood in the lower extremities is that the pulmonary system becomes less efficient and blood delivered to the head is less well oxygenated than normal. This effect compounds the perceptual anomalies due to low head-level blood pressure, and introduces a time delay into the physiological consequences of G-stress. For rapid onset acceleration, even if head level pulse disappears entirely, the pilot still has several seconds of useful consciousness while his brain consumes its oxygen reserve. On the other hand, if the pilot has been exposed to rapidly fluctuating or continuous low levels of G-stress, his blood oxygen reserves may already have been depleted when a G-peak reduces his head-level blood pressure. Consequently a pilot's G-tolerance decreases with time of exposure.

Lower Body Negative Pressure can reproduce many of these perceptual effects very faithfully because it acts to reproduce the primary physiological effect of acceleration, the pooling of blood in the lower extremities. When atmospheric pressure over the legs and lower abdomen is decreased, the pressure differential between the upper body and the lower body forces blood downward into the low pressure region. The blood vessels in the LBNP region distend under the pressure of this blood, thus reducing the working volume of blood in the upper body. Consequently, the head level blood pressure declines, just as in Gz-exposure.

Because of this parallel to the effects of G-stress, LBNP has acquired the status of a standard analog for gravity in spaceflight research and operations. Both the Unites States and the Soviet Union have used LBNP very successfully as a way of counteracting the cardiac deconditioning which occurs in astronauts exposed to microgravity for extended periods. The use of LBNP as an analog for the G-stresses encountered in aerobatic flight have not been systematically studied, however, so there is no consistent data on which to base a comparison between the effects of high, fluctuating G_z and those of LBNP.

B.2 Mechanization of LBNP Cuing Devices

B.2.1 General Considerations

Production of a partial vacuum over a subject's legs and lower abdomen is a relatively straightforward matter, whether the subject is seated or supine. Several "LBNP Boxes" have been constructed for various purposes, usually quite inexpensively. They generally consist of a metal or plywood box with some sort of adjustable seal closing around the subject's waist or upper thighs, and connected to a high volume vacuum source (such as a household vacuum cleaner) and suitable instrumentation. Since relatively low pressure drops are required (seldom more than 10% of atmospheric pressure), leakage around the seals is not critical to the design provided the vacuum pump can move the leakage volume.

A part-task trainer or acceleration familiarization training device based on LBNP could therefore be implemented very easily. In such a device, the trainee would sit in an appropriate seat with his lower body enclosed by the LBNP box. A waist seal, such as the iris type used by several previous researchers, or the kayak skirt type described below, would close the top of the box. Obviously, the trainee's access to objects and controls below waist level would be prevented, but in a part task trainer, this limitation may be quite acceptable. Installation of rudder pedals would not be difficult and a sidestick controller seems perfectly appropriate to most modern fighter pilots. A simple, microprocessor based flight simulator with a single forward visual display and an instructor console for scenario control, LBNP system control, and physiological monitoring would complete the configuration. It will be important to provide some sort of visual scene (not necessarily moving with the simulation) in the trainee's peripheral visual field simply to allow him to appreciate the early stages of G-dimming.

In practice, the instructor could begin by simply exposing the trainee to progressive levels of LBNP and calling his attention to the resulting sensations and their correlation to acceleration effects. The trainee would then progress to flying the simulator through various high-G maneuvers with the LBNP unit providing

acceleration cues. With appropriate coaching by the instructor, the trainee could then safely probe the margins of his personal acceleration tolerance envelope, learning to monitor his physical responses to acceleration and thereby extracting maximum personal performance.

An LBNP device of this sort, but without the simulator, could also be used simply for routine G-exposure either to familiarize pilots with the sensations and physiological effects of G forces or to provide acceleration conditioning on an ongoing basis. For this type of activity, an LBNP device can provide some of the utility of a human centrifuge, but at a price which would make it practical to provide the units at fighter bases throughout the world--including aboard aircraft carriers.

Since some kind of hard structure is required to support atmospheric pressure over the active area of an LBNP device, LBNP trousers suitable for use in a mission simulator are a greater design challenge than a simple LBNP box. Trousers, such as those constructed by Tripp (1988), with stiffening rings, integral boots, and a waist seal--something like a space suit--are certainly feasible, but will inevitably seem unnatural to the pilot trainee. The alternative of simply sealing off the cockpit below the pilot's waist is certainly feasible in a sidestick controlled airplane such as the F-16, but again, the arrangement may seem unnatural to the trainee. The utility of an LBNP cuing module may well outweigh these disadvantages, however.

The amount of pressure reduction over the lower body--the so-called "negative pressure"--required for effectiveness in an LBNP device is actually quite small. According to Stevens and Lamb (1965), 80 Torr of LBNP is sufficient to produce symptoms of impending syncope; that is, it is roughly equivalent to about 5 G of acceleration. Eighty Torr is barely over 10% of sea level atmospheric pressure (760 Torr); a reduction of atmospheric pressure by 80 Torr is roughly equivalent to an altitude increase of only 3,000 feet. The main technical challenge of the design of an LBNP cuing module is the matter of controlling the LBNP chamber pressure. In order to simulate G-onset rates of up to 10 G/sec, at least 100 T/sec of controllable pressure change rate will be required.

B.2.2 Design Considerations

B.2.2.1 General Configuration

For an LBNP cuing module, particularly a box type unit, it will be important to move large quantities of air in and out of the device quickly. One way to achieve this end without simply resorting to an expensive, high volume pump, is to provide a vacuum reservoir as part of the vacuum system as illustrated in Figure B.2-1. Under steady state conditions, the pump works on

evacuating the chamber. When the simulation requires a rapid evacuation of the LBNP chamber, the vacuum valve is opened as necessary, allowing air to flow out of the LBNP chamber. When the simulation requires filling of the LBNP chamber, the bleed valve is opened as necessary, the vacuum valve remaining closed. The vacuum pump can therefore be sized to accommodate the average air throughput requirements of the system, while the reservoir can be sized (depending on the ultimate pressure differential the pump can produce) to allow maximum application of LBNP with no pump assistance. The two valves, the bleed valve to atmosphere and the vacuum valve to the reservoir, would be under the control of a servo system which minimizes the difference between the pressure within the LBNP chamber and the pressure commanded by the simulation.

B.2.2.2 Waist Seal Design

Several successful waist seals for LBNP devices have been constructed, most involving moving slats which support a sheet rubber diaphragm forming the actual seal. A more flexible design, similar to the spray skirt of a kayak, is shown in Figure B.2-2. The top of the LBNP chamber, at subject waist level, is fitted with an oval lip. The subject wears a shirt with a rubberized skirt with a drawstring at its hem. When the subject is seated in the LBNP module, he pulls the skirt over the lip of the chamber and tightens the drawstring, thus forming a seal. The waist of the skirt, where it joins the shirt, fastens snugly with a Velcro closure around the subject's waist and is held in place vertically by the shirt itself. For the comfort of the subject, the shirt should be made of a breathable fabric, only the skirt being rubberized. When the chamber is evacuated, atmospheric pressure will push the skirt waist against the subject's trunk forming a seal. The force generated by the air pressure on the skirt will be transmitted to the subject's chest, back and shoulders providing an additional somatosensory acceleration cue. The magnitude of this force will be quite small compared to real-world forces, of course, but will provide an appropriately scaled cue. The magnitude of the force is proportional to the area of the skirt between the subject's waist and the chamber lip. In order both to transmit the force evenly into the shirt and to insure a good air seal at the waist, it may be necessary to lubricate the top of the skirt and the subject's skin with mineral oil.

B.2.2.3 Vacuum System Design

The basic system configuration for an experimental LBNP device is shown in Figure B.2-1. Figure B.2-3 shows the dimensions of the LBNP Chamber. The entire seat and LBNP box unit is to be constructed of 3/4 inch plywood with braces of 1x4 and 2x4 lumber. One side of the box is easily removable both for ease of entry and for safety. The removable side is fastened with trunk latches and sealed with a rubber gasket. The seat itself is not adjustable, although cushions of varying thicknesses may be used to make minor accommodations of subject dimensions. Although the pedal mechanism must be adjustable if pedals are to be used in the flight simulator, their use does not appear to be an absolute necessity, at least for experimental purposes.

Figure B.2-4 shows a schematic diagram of the vacuum system for the LBNP module. The system must be capable of reducing the pressure of the LBNP chamber (-DP) by 100 Torr within 1 second, and of regulating the pressure to within 2 Torr. Since the volume of the LBNP chamber is about V1=7.4 cubic feet (CF), to reduce the chamber pressure P1 by 100 T to P1=660 T, the volume of air (DV) to be removed at 660 T is

$$DV=V1\frac{-DP}{P1}=-1.1CF$$

Since the desired pressure change rate is dP1/dt=-100 T/s, the volume flow rate (Q) required is

$$Q=\frac{dV}{dT}=V1\frac{-dP1/dt}{P1}=-67CFM$$

This flow rate must be produced by the reservoir; that is, the reservoir must absorb 1.1 CF in 1 second (DV). In doing so, the pressure of the reservoir, P2, must increase from its initial value to a final value which retains some margin of pressure difference (DP2) to maintain the flow rate. Taking the initial reservoir pressure as P2I = 610T (150 T below atmospheric pressure) and final pressure difference to be DP2 = 25 T (0.5 PSI), then the final reservoir pressure is P2F = 635 T. Thus the volume of the reservoir must be

$$V2=DV\frac{P2F}{DP2}=28CF$$

This figure implies a very manageable 3 ft cube.

Now, the pipe and vacuum valve conducting air from the chamber to the reservoir must be able to sustain a flow rate of 67 CFM at 660 T under a pressure head of 25 T (0.5 PSI). Sizing the pipe for this purpose is complex and depends on the details of the configuration, but plausible estimate can be made. Friction loss in a straight pipe of reasonable size will be very small over the lengths required for this application. Taking the distance between the chamber and the reservoir to be 5 feet, frictional pressure loss at 70 CFM in a 2 inch pipe is only 0.7 T. (This figure is based on standard plumbing design tables.) The bulk of the pressure required to drive a flow is frictional loss at the inlet and over the valve gate. The standard design figure for 2 inch pipe at 3,500 FPM (76 CFM), with the inlet at atmospheric pressure is about 2 inch HG or about 50 T. Hence, 2 inch pipe is a little too small for the LBNP application. Three inch pipe should provide adequate conductance.

In a crude experiment, a home vacuum cleaner pulled about 20 CFM through 60 inches of 3/4 inch PVC pipe with a pressure drop of about 25 T. This corresponds to a Reynolds number of about 36,000--well into the regime of turbulent flow, but requiring a flow velocity of only about 100 FPS. Using the principle of dynamic similitude, for the same tube length, the required diameter, Dr, is

$$Dr = \frac{Qr}{Qexp} Dexp = \frac{67\ CFM}{20\ CFM} 0.75\ inch = 2.5\ inch$$

Thus, 3 inch PVC pipe over a length up to 5 feet should be adequate.

The vacuum pump must be able to pull an ultimate vacuum of -150 T (gauge). This is more than the turbines of most household vacuum cleaners can do, but commercial shop vacuum cleaners are capable of this performance. The flow rate of the pump must be enough to overcome any system leakage and to carry the average bleed rate. This average depends on the experimental pressure profiles. Typical shop vacuum cleaners can move about 20 CFM under full load. Since the maximum required pumping rate is about 70 CFM, and the minimum is, say, 3 CFM for leakage, then the maximum duty cycle at 100 T/sec is 25%. This figure seems entirely reasonable.

The reservoir could be constructed very easily out of 3/4-inch plywood with an internal frame of 2x4 lumber. This approach will provide an easily worked surface for directly mounting a shop vacuum cleaner motor. A four foot cube is a convenient size and provides more than enough volume.

The plumbing can be constructed of 3-inch PVC pipe. The servo valves can be electrically operated wide aperture types to provide rapid response and high conductance.

B.2.2.4 Pressure Control

Pressure control of either an experimental or production LBNP module must be provided by servo control of the vacuum and bleed valves as shown in Figure B.2-1. A solid state differential pressure transducer mounted on the LBNP chamber transmits the chamber gauge pressure, P1, to the servo system where it is compared to a computer commanded value, Pc. The pressure error, DP, is then sent through an appropriate loop filter to the valve controller. Negative error (high chamber pressure) results in opening of the vacuum valve; positive error (low chamber pressure) results in opening the bleed valve. The minimum slew rate of the plant is much better than 100 T/sec over most of its range, so pressure changes of that magnitude should normally be possible. Rapid action valves (rise times less than 0.1 sec, will preclude significant overshoot. Valve selection is the critical element of the design.

For simplicity, the error detector and loop filter should be implemented as analog circuits, but the commanded pressure derives from a computer. This computer is either the simulation host, or in the case of the early experiments, a computer used to control the experiment. In the non-simulation based experiments, the desired pressure profiles are all piecewise linear and will be easy to program. In a simulator environment, the computer will perform the G to LBNP transformation and command instantaneous desired pressure to the servo system.

B.2.2.5 Peripheral Vision Loss Measurement

Since the loss of peripheral visual sensitivity is one of the primary cues LBNP is intended to stimulate, it will be important to measure peripheral vision loss as part of the evaluation of LBNP. Figure B.2-5 shows a suitable arrangement of equipment for this purpose. An array of LEDs is mounted on a frame at specific angles from the subject's optical axis. While the subject fixates on a central point the researcher sequentially illuminates LEDs starting from large angles until the subject can detect a light in his extreme peripheral field.

B.3 Proposed Experimental Program

B.3.1 Objectives

The ultimate objective of the LBNP cuing experimental program is to develop a set of design guidelines for simulators utilizing this technique for acceleration cuing. The more immediate objective, however, is to determine the feasibility and

effectiveness of using LBNP as an analog for aircraft acceleration. In addition to the feasibility question, the safety of LBNP must also be addressed before design guidelines can be formulated.

Since the construction of LBNP equipment poses no significant engineering challenges, the basic feasibility question is that of the nature of the correlation between the effects of dynamic accelerations and of LBNP. The research effort must answer several specific questions:

1. How do the physiological effects of G_z correspond to the physiological effects of LBNP?

   - Is the cardiovascular system affected similarly?
   - Does G-dimming occur similarly?
   - Is blood oxygenation affected similarly?
   - Does LBNP exposure increase G-tolerance?
   - Are there any anomalies (such as the diastolic anomaly)? Can they be avoided?

2. In spite of any differences, do LBNP-induced cues correspond in a meaningful way with acceleration cues?

   - What, quantitatively, is the relationship between LBNP and G_z?
   - What is the difference between the static and dynamic environments?
   - Can LBNP track acceleration changes up to 10 G/sec?
   - Does LBNP induce undesired motion or attitude sensations?
   - What effect does using a G-suit have on LBNP? How should the G-suit be simulated in an LBNP device?
   - Is straining compatible with LBNP? Does straining have the same effect under LBNP as under G?
   - Does LBNP feel like acceleration? Will pilots accept it?

3. How safe is LBNP?

   - What specific risks are there?

- o How do these risks correlate to the risks of G exposure?
- o What protective measures are available?

4. What are the design criteria for a useful LBNP cuing device?

   - o What is the transfer function from G to LBNP?
   - o How should LBNP be applied?
   - o How should the production of LBNP be coupled with other acceleration cues?

B.3.2 Experimental Approach

The experimental program should proceed in five distinct phases aimed at meeting the stated objectives. The program begins with a period of equipment design and fabrication, proceeds through three stages of experimental effort, and ends with a period of evaluation of the experimental results and formulation of a set of LBNP design criteria. The core experiments involve first evaluating the effects of LBNP in steady state, then performing a similar series of experiments in a dynamic environment, and finally, adding simulation to the experimental system to evaluate the issues of fidelity and pilot acceptability.

The experimental runs will require a pool of subjects and an experienced staff, including a medical monitor.

An outline of the proposed experimental program follows.

1. Construct an LBNP device. The device must be suitable for seated use, and include appropriate instrumentation.

   - o Analyze performance requirements.
   - o Design, build and test the device.

     -- Chambers
     -- Plumbing
     -- Pumping System
     -- Control Valves
     -- Pressure Sensing System
     -- Pressure Servo System
     -- Safety interlocks

- Prepare necessary instrumentation.

  -- Blood pressure: heart level, eye level
  -- Heart rate
  -- Respiration rate
  -- Oxygen saturation
  -- Visual Field Detector

- Prepare research protocols and comply with regulations for use of human subjects.

2. Perform Steady-State LBNP Evaluations.

- Run 5 subjects through 10 runs each, no more than one run per day for each subject.
- Apply LBNP at a rate of 1 T/sec, pausing at 10 T steps for 50 sec up to blackout.
- Apply LBNP at 1 T/sec directly to an ending level of a multiple of 20 T. Hold for 50 sec.
- Apply LBNP at 50 T/sec directly to an ending level of a multiple of 20 T. Hold for 50 sec.
- Repeat the experiments using G-suits. Use preliminary results to determine a scale factor for G-suit pressure.
- Repeat the rapid-onset experiments using straining and using combined G-suits and straining.
- Repeat the rapid-onset experiments using positive pressure breathing.
- Evaluate data (and perform additional experiments as required) to devise a preliminary G to LBNP transfer function.

3. Perform Dynamic LBNP Evaluations.

- Run 5 subjects, 3 times each, no more than one run per day for each subject.
- Using the transfer function developed from the previous experiments, run the Simulated Air Combat Maneuver (SACM) using LBNP as an acceleration analog.
- Analyze results and modify transfer function as resources permit.

- o Analyze results and propose a "validated" transfer function or other map from G to LBNP.

4. Evaluate the fidelity of LBNP.

- o Add a simple flight simulator to the LBNP Box.

- o Have each subject fly a standard sequence of high-G maneuvers, and record their impressions of the fidelity and acceptability of the G-cuing.

- o Allow each subject to fly 20 minutes of free-form flight and record their impressions of the fidelity and acceptability of the G-cuing.

- o Within the constraints of resource availability, evaluate and implement any recommendations by the subjects for improvement in the cuing fidelity.

5. Evaluate Results

- o Review all results and prepare a final recommendation for the map from G to LBNP.

- o Analyze the risks involved in LBNP application.

- o Prepare a report presenting the results of the study and presenting a paradigm for LBNP as an acceleration cuing technique.

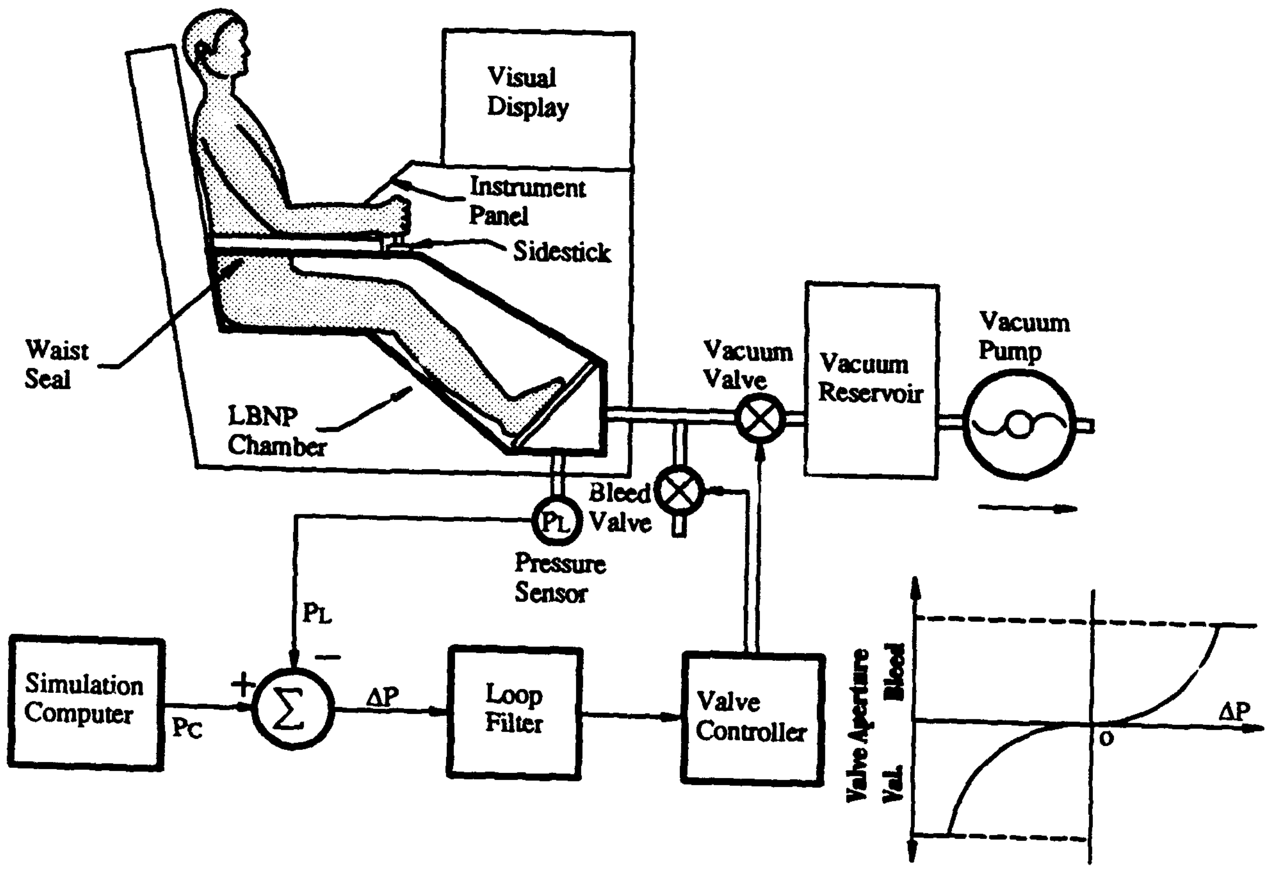


Figure B.2-1. Schematic diagram of an experimental LBNP chamber.

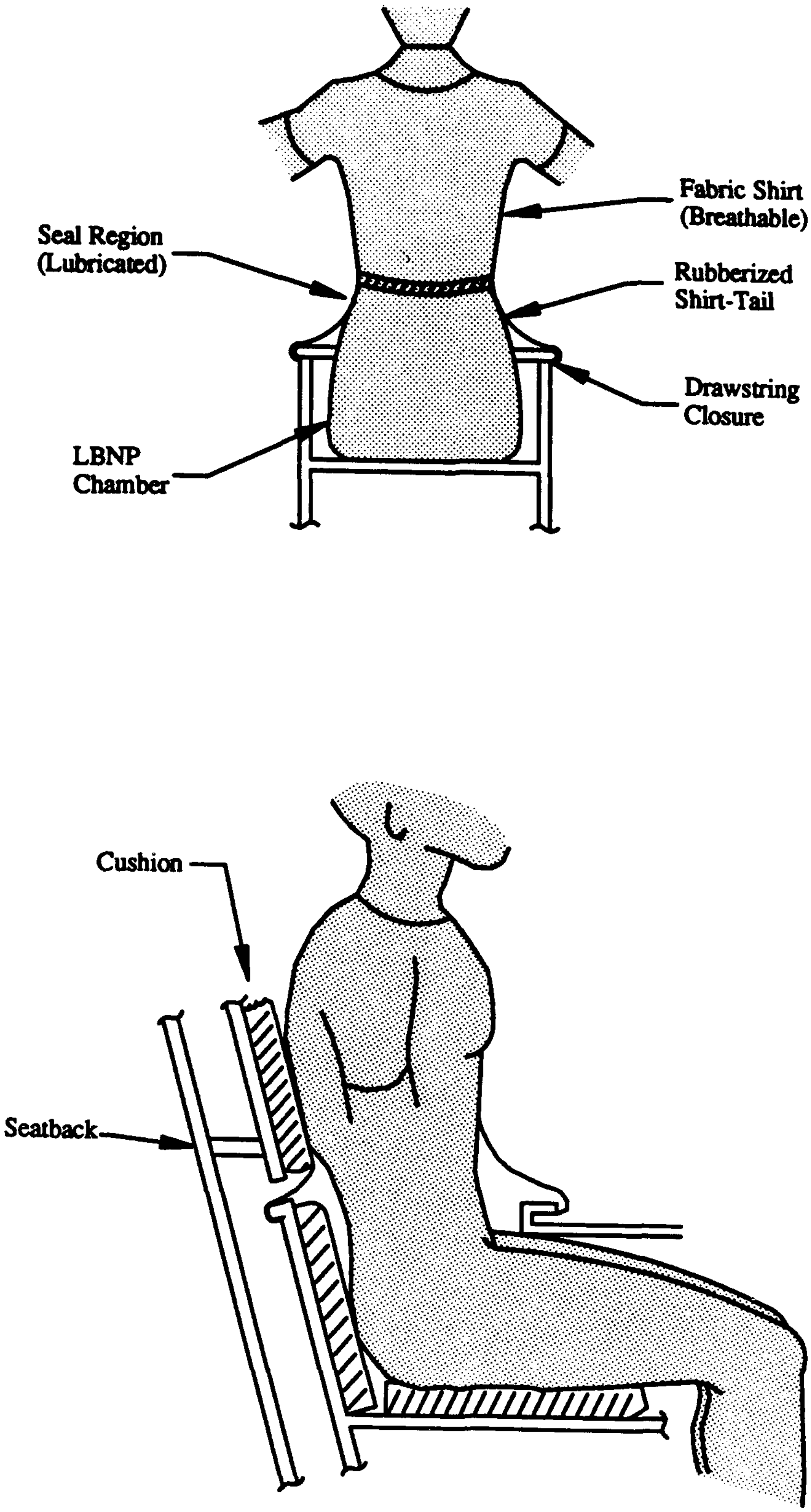


Figure B.2-2. LBNP chamber waist seal design.

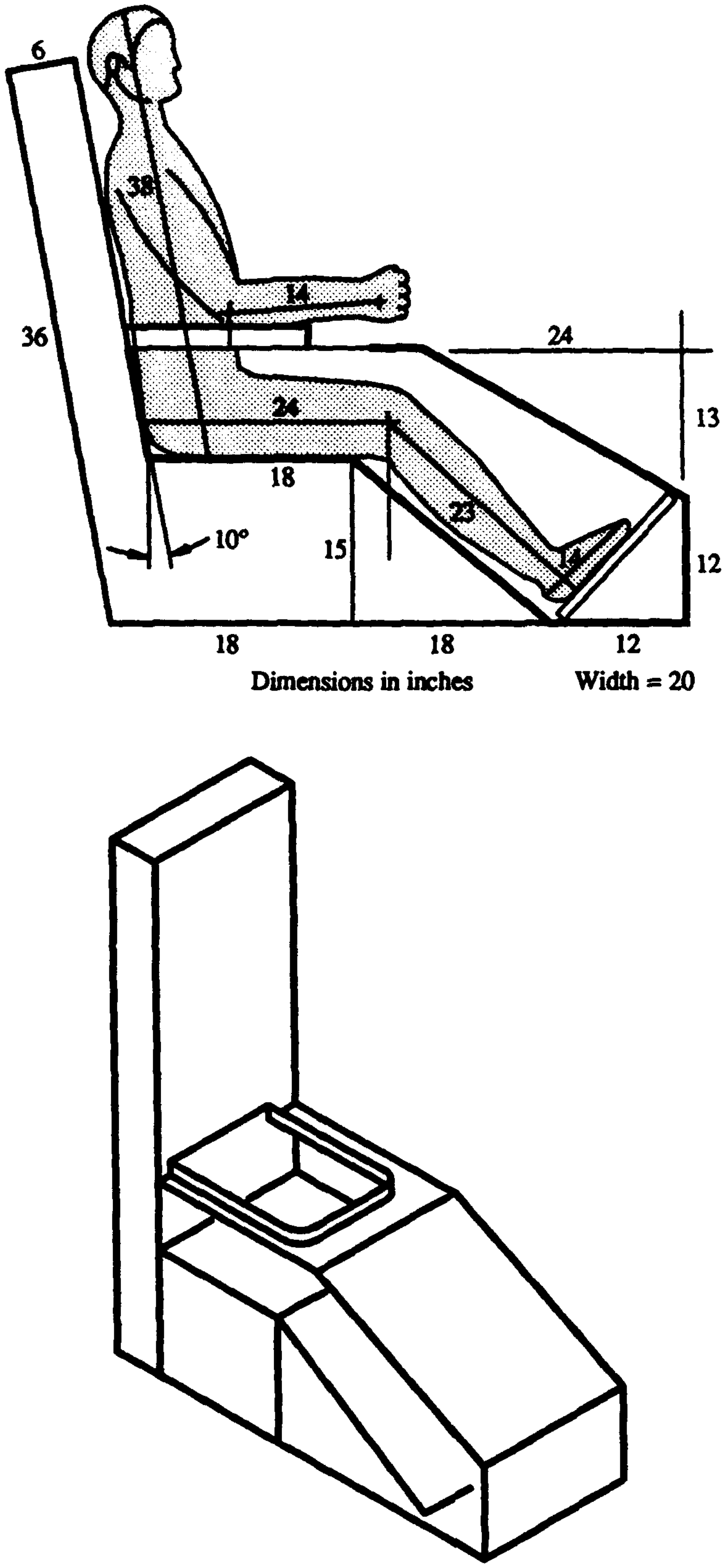


Figure B.2-3. Configuration of the LBNP chamber.

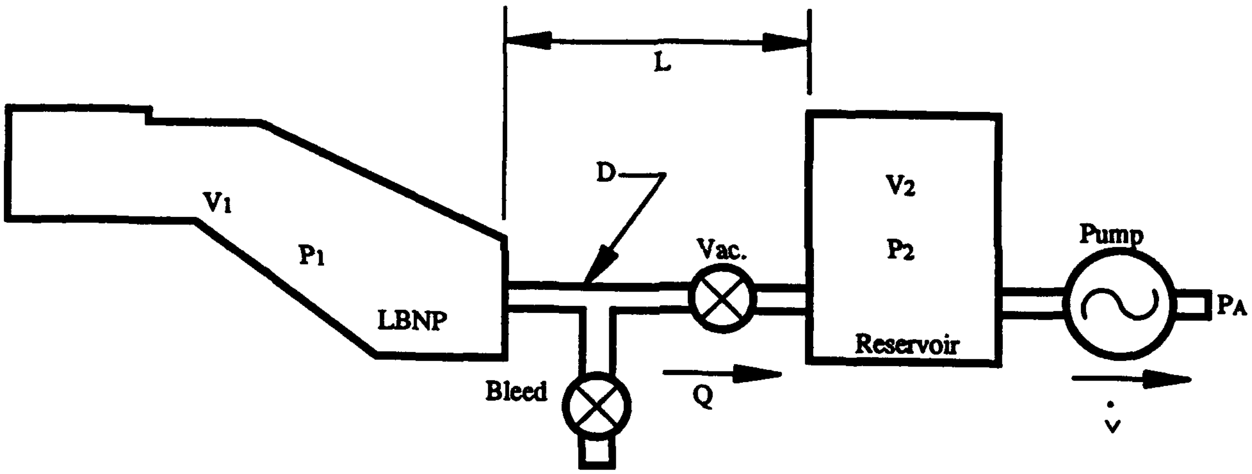


Figure B.2-4. Schematic diagram of the LBNP vacuum system.

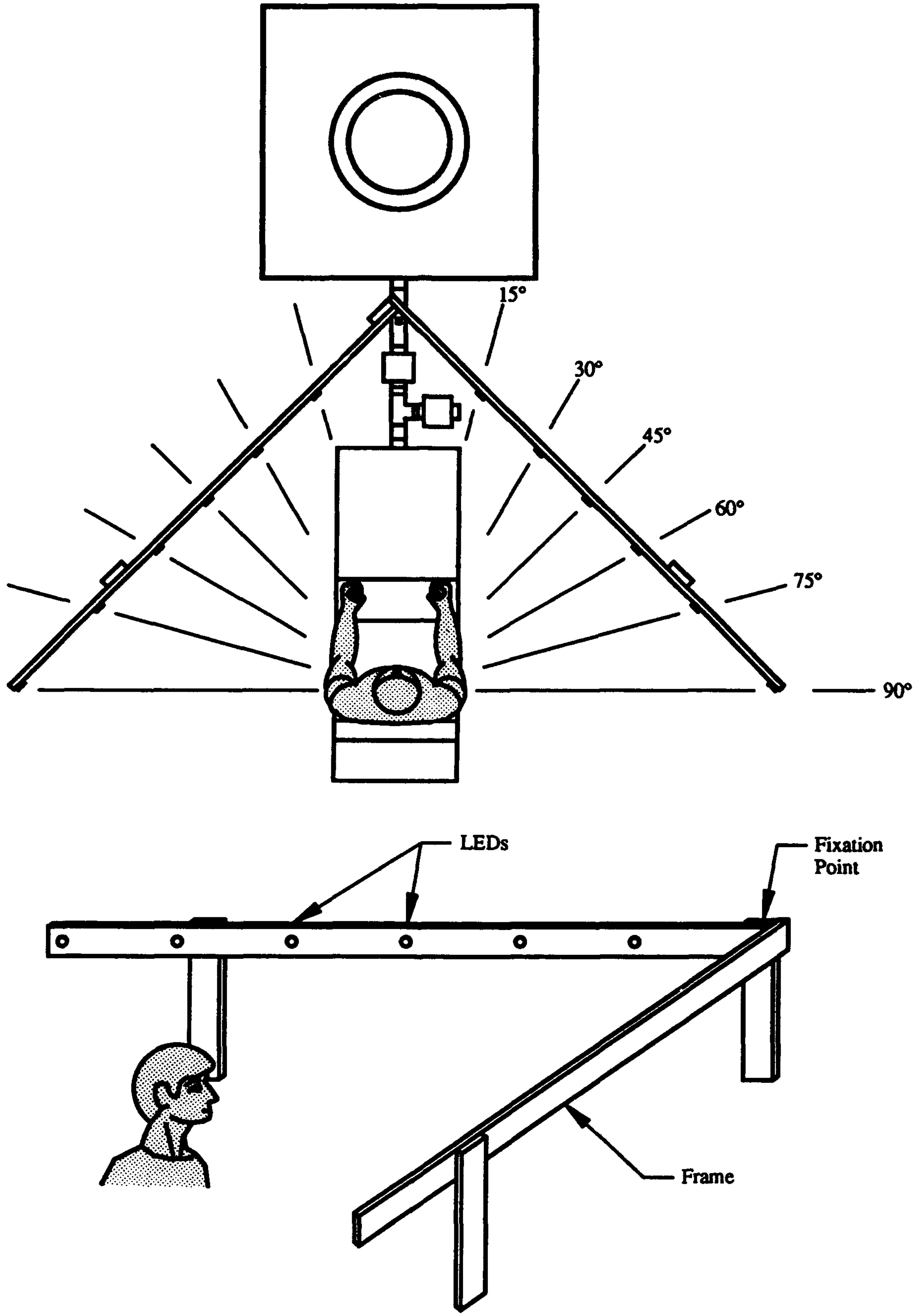


Figure B.2-5. Apparatus for measuring peripheral light loss.

Appendix C. An Experimental Thermal Cutaneous Cuing Module

C.1.1 Physiological Background

The skin possesses a variety of specialized structures that transform environmental energy into neural activity. Most of these structures, or cutaneous receptors, generate a neural potential when mechanically deformed. The extent and pattern of deformation--or strain for a given stress--is determined by the mechanical characteristics of the receptor and the surrounding tissue. In any localized region of tissue there are receptors that vary widely in morphology and mechanical characteristics. Thus, localized deformation of the skin gives rise to a multi-dimensional pattern of neural stimulation. In addition, the tissue that surrounds a given receptor type can vary from one body region to another. It follows that there is not a simple mapping between receptor type and sensitivity of particular body regions to mechanical stimulation (Sherrick and Cholewiak (1986)). Sensitivity to, and attendant perception of, mechanical stimulation is revealed by psychophysical data. However, in the absence of such data it is useful to know the relative size of different receptor populations in a given region of the body. One could speculate about the sensitivity of a given region based on the sensitivities of the predominant receptor types alone.

Many cutaneous receptors are temperature sensitive. Thermal stimulation of these receptors will occur when there is a sufficient temperature difference between the skin and the environment. Some receptors show sensitivity to temperature with little or no sensitivity to mechanical stimulation; others are sensitive to both thermal and mechanical stimulation (Hahn (1974)). These receptor populations are intermixed in most regions of the body. Thus, thermal and mechanical stimulation are linked both microscopically and macroscopically. This is relevant whenever there is contact between the skin and a substance that is not at skin temperature. One cannot draw conclusions from the physiological data about the perception of temperature and mechanical contact; psychophysical data are required. However, the physiological data do suggest that synergistic thermal and mechanical stimulation is worth serious consideration in the development of a cuing module that can modify the perception of mechanical contact.

C.1.2 Psychophysical Response Characteristics

Response characteristics of a system are generally defined in terms of the effects of spatial and temporal variation in stimulation on a system's behavior. The so-called pressure sensitivity of the skin is determined primarily by the spatial gradient of skin deformation (which is generally determined by a spatial gradient in pressure). Numerous studies (cf. Sherrick and Cholewiak (1986)) have demonstrated that pressure and

vibration sensitivity vary from one body region to another, and that they do not necessarily covary. Data on pressure sensitivity of the buttocks are lacking.

Spatial and temporal variation in stimulation can interact in the perception of events. A familiar example is perceiving the direction of a sound source via the time difference in the arrival of the sound at the two ears. A similar phenomenon obtains in cutaneous perception (von Bekesy (1959)). With an appropriate time difference, two discrete cutaneous sites of stimulation can give rise to the perception of a single intermediate site of stimulation. One can simulate a continuum of contact positions by manipulating the time (or phase) difference between two fixed sites of stimulation. This technique of bi-cutaneous stimulation has been exploited, experimentally, as feedback about joint angle in the control of an artificial limb (Mann and Reimers (1970)).

Magnitude and temporal variation in cutaneous stimulation interact to determine sensitivity to vibration. Below 200 Hz, magnitude must be increased as frequency is decreased to maintain a given level of sensitivity. The rolloff is about 12 dB/octave between 40 and 200 Hz (Verillo (1975); stimulation of the palm of the hand, sole of the feet, or hairy skin of the forearm). This indicates a system that is sensitive to accelerative deformation of the skin. Below 1.3 Hz, however, the rolloff is only 3 dB/octave (Flach, Riccio, McMillan, and Warren (1986)); stimulation of the buttocks. This indicates a system that is intermediate between a static deformation and deformation velocity sensor (cf. Scott Blair (1944)). There are few data for the frequency range between 1.3 and 20Hz. This is unfortunate since fixed-wing aircraft produce significant vibration in this range (cf. Boff and Lincoln (1988)).

A limited amount of data are available on the spatial and temporal factors that influence cutaneous sensitivity to thermal stimulation. Perceived temperature is determined primarily by the difference between the temperature of the stimulation (e.g., the surface of an object in contact with the skin) and "physiological zero" (i.e., essentially the temperature of the skin). Several researchers (cf. Sherrick and Cholewiak) have shown that the psychophysical relationships are similar, but not identical, for warm and cold temperatures and that physiological zero can gradually adapt or change toward higher or lower temperatures when the skin is in contact with an object that is not at skin temperature. The influence of physiological zero on the perception of warm and cold is maintained over a range of five degrees C in the adapting temperature. Adaptation thus imposes a low-frequency limit on sensitivity to variation in temperature. This low-frequency limit gives rise to a rate-sensitive region in temperature sensitivity from about 0.01 to 0.10 deg-C/sec. Temperature sensitivity is essentially

rate-independent at higher rates of temperature change. Several studies (cf. Sherrick and Cholewiak) have also shown that temperature sensitivity is influenced by the area of contact.

With respect to thermal stimulation, the cutaneous system acts as spatial integrator. Integration can also occur over spatially separated sites of thermal stimulation. This is consistent with the fact that spatial localization of thermal stimulation is diffuse and somewhat labile. The cutaneous system also integrates thermal stimulation over short time intervals. Given that it is also subject to adaptation, it could be described as a leaky integrator. In sum, there are a variety of ways to manipulate perceived temperature: duration, extent, and magnitude of thermal stimulation. It should, then be possible to trade off these effects so that the various parameters of thermal stimulation could be manipulated without changing perceived temperature. Several studies have shown that magnitude can be traded off with either extent or duration of stimulation to yield identical sensitivity.

C.1.3 Interrelations Among Thermal and Mechanical Sensitivity

Physical and physiological considerations suggest nontrivial interactions between thermal and mechanical sensitivity. Such multimodal interactions are the rule, rather than the exception, during interactions between a perceiver and the environment. Interactions with the environment involve the creation, dissipation, and transformation of various forms of energy. Animals generally have a variety of sensory systems with which to detect these energy transactions with the environment. One should not be surprised if there were some general rules concerning perception in the context of concurrent multimodal patterns of stimulation. Studies in multimodal perception have not been popular in the latter half of this century because of the pervasiveness of reductionistic epistemologies. However, many experiments in multimodal perception were performed in the early years of psychophysics. Many of the results are summarized and organized in a classic review by Ryan (1940). Although he did not address interactions between touch and temperature specifically, his analysis has clear implications for the problem at hand.

Ryan (1940) discussed both qualitative and quantitative interactions among the sensory systems. Among the more robust classes of quantitative interactions are the spatial inductive effects. These are situations where there is an interaction between the perceived locations of temporally concurrent patterns of stimulation in different sensory systems. A familiar example is the "ventriloquism effect" whereby the perceived location of a voice is "captured" by the optically specified location of a synchronously moving mouth that is distant from the actual sound

source. There are a number of analogous effects involving other modalities. It is generally the case that the modality in which localization is more precise and stable influences the modality in which localization is more di.fuse and labile. Repetition strengthens the effect. In addition, the effect is somewhat resistant to small temporal mismatches (on the order of 100 msec.) as long as the patterns remain similar. This phenomenon suggests that the location of mechanical stimulation could influence or capture the perceived location of thermal stimulation (a cutaneous spatial inductive effect). Similarly, precise co-location of mechanical and thermal stimulation may not be necessary for unified cutaneous percept.

Another class of interactions discussed by Ryan (1940) are the dynamogenic effects. These are situations where stimulation of one modality influences the sensitivity in another modality. The likely causes of such effects include arousal, directing or focusing attention, informational redundancy, and physiological synergy. All these factors are probably involved in the sensitivity to concurrent thermal and mechanical stimulation. A relevant example is the increase in perceived roughness caused by increase in skin temperature. These data suggest that temperature variations can be used to modify perception of spatial gradients in pressure. Another, perhaps related, effect is the "Weber illusion" whereby a cold object placed on the skin feels heavier than a neutral object and sometimes feels heavier than a warm object (Stevens (1979); Stevens and Green (1978)). These data are consistent with those of Sullivan (1923, 1927) concerning the perception of liquids and solids. Cutaneous perception seems to be strongly influenced by pressure gradients at the edge of the objects or liquids, and temperature seems to increase sensitivity to these gradients. For example, a liquid is perceived as more viscous, and a solid as harder, when it deviates from skin temperature, especially when the solid or liquid is cooler. Finally, there can also be qualitative interactions among sensory systems. In these cases, there is an "emergent property" of multimodal perception, that is, a property that is not perceived when only one of the sensory systems is stimulated. These phenomena are generally due to objective properties of the environment (cf., Ryan (1940)), or the animal-environment interaction (cf., Gibson (1966)), that structure different forms of energy in different ways. These intermodal relations are specific to, and therefore provide information about, the environment. While there has been recent progress in this approach to multimodal perception (Riccio and Stoffregen (1988)), it has not been applied to cutaneous sensitivity to thermal and mechanical stimulation. However, older work on the so-called "touch blends" is relevant (Bentley (1900); Katz (1937); Scott Blair (1944); Titchener (1909); Tung (1921)). In these phenomena, pressure and temperature interact to determine whether a material feels wet, clammy, sticky, or tacky. For example, a soft material that generates a shallow

pressure gradient may feel clammy if it is also cold.

It is also worth noting that there may be important interactions between pressure and vibration in cutaneous perception. One possible source of interaction could be generated by asymmetrical impedances in the body tissues For example, if stress-strain relationships are different for compression and tension in the skin (as is almost certainly the case) then vibrations would be asymmetrical. Vibrations could be asymmetrical for other reasons (e.g., inherent in the external disturbance). But asymmetries of vibration that covary with pressure magnitude could be specific to, and therefore provide information about the mechanical contact event.

C.1.4 Synergistic Thermal-Mechanical Cuing

It has been suggested that thermal cutaneous stimulation could be a valuable alternative or adjunct to mechanical stimulation with the G-seat. This possibility follows from the conjecture that a spatiotemporal pattern of cutaneous thermal (or thermal-mechanical) stimulation may adequately simulate a spatiotemporal pattern of cutaneous mechanical stimulation typical of flight. If this were the case, it might be possible to avoid the unnatural consequences of conventional G-seat simulation. These consequences include (a) an inverse relation between magnitude and spatial extent of mechanical stimulation or (b) forces of a magnitude large enough to move the pilot's body in the wrong direction. An (admittedly speculative) strategy to eliminate the problems mentioned above would be to manipulate magnitude of the contact event with spatially-diffuse thermal stimulation and to manipulate location of the contact event with low-pressure mechanical stimulation. Manipulation of magnitude would exploit the apparent thermal enhancement of sensitivity to pressure gradients. Spatial extent of mechanical stimulation would not have to be reduced in order to increase the magnitude of the perceived contact force (cf. Cardullo (1989)). The current location of G-seat actuators could be retained; in fact, this would be desirable given the location of weight bearing areas while sitting (cf. Zacharakow (1988)).

A slight modification might be possible for use of g-seat thigh panels for lateral and roll cuing. Time differences between ischial tuberosity actuators and thigh panels could be used to produce an apparent motion of the center of pressure between the central and lateral regions of the buttocks. Vibration of the actuators (with controllable phase differences) would allow for the continuous low-frequency variation of center of pressure. Vibration could be in the frequency range produced by fixed-wing aircraft. Moreover, if asymmetry of vibration could be manipulated it might provide cues about G magnitude. Cuing of vibration, acceleration, and attitude would thus be thoroughly integrated. In any case, thermal stimulation would presumably be

available to enhance cuing of G magnitude. Note that thermal stimulation would not have to change location because it is not well localized. To the extent that thermal stimulation has an identifiable location, it may be subordinate to the location specified by the mechanical stimulation.

If time differences between the actuators are not used to manipulate apparent center of pressure, it might be sufficient to manipulate the relative magnitude of stimulation at the thighs and ischial tuberosities. This could be attempted with more localized Peltier-effect modules at each of these sites. The advantages of lateral and roll cuing with either the vibration or temperature difference strategies is that inappropriate movements in the pilot's body are avoided. Such movements have been implicated as a serious limitation of dynamic seat cuing (Riccio (1989)). It is important to note that none of the (highly speculative) cuing strategies suggested in this section would interfere with visual simulations of nonrigid motion of the pilot relative to the aircraft (Riccio (1988)). In fact, vibration cuing may actually enhance the simulation of pilot motion given the transmission of seat vibration to the head (cf. Boff and Lincoln (1988)).

Some consideration should be given to the perception of temperature, as such, during synergistic thermal-mechanical cuing. For example, there may be some unpleasant touch-blends in the seat of the pilot's pants. However, it may be possible to develop thermal cuing strategies that maximize thermal enhancement of pressure sensitivity and minimize variations in perceived temperature. Perhaps one could exploit the tradeoffs among the factors that effect temperature perception. For example, spatially localized thermal stimulation in the neighborhood of the ischial tuberosities and lateral thighs could be balanced by an opposing effect of diffuse thermal stimulation. The localized thermal stimulation could be temporally synchronized (at least in the lower frequency range) to the associated mechanical stimulation. It seems plausible that spatial and temporal proximity would give the localized thermal stimulation a greater effect on pressure sensitivity.

Successful thermal enhancement of sensitivity to pressure gradients would have other implications for force cuing. It may be possible to exploit this technique in the shoulder harness. The advantages would be similar to those for the seat. While the ideas presented in this section are speculative, they are sufficiently specific to be tested experimentally.

C.2 Implementation

Application of a temperature stimulus to the pilot's seat is a fairly straightforward matter. Although electrical resistance heaters and standard refrigeration techniques could easily be

used, a thermoelectric device provides both heating and cooling very conveniently in a single, compact package with no moving parts.

A thermoelectric heat pump moves heat through the action of the thermoelectric phenomenon called the Peltier Effect, which occurs when an electric current is passed through a circuit containing dissimilar conducting materials. Figure C.2-1 shows such a circuit composed of a piece of p-type semiconductor connected between two copper electrodes, thus forming two thermoelectric junctions. The power supply causes current to flow through the circuit from the positive terminal to the negative terminal. The conduction process in the metal is normal metallic conduction involving drift of conduction electrons; but in the semiconductor the conduction process involves hole flow. Since the holes are thermally activated quanta, they carry heat with them as they flow. Consequently the current injection junction is cooled while the current extraction junction is heated. The action is entirely analogous to conventional refrigeration in which heat is transported by a working fluid undergoing different pressure, volume and temperature change processes at the evaporator and condenser coils. The configuration shown in Figure C.2-1 will not make a very efficient heat pump, however, because the high thermal conductivity of the copper connector thermally short circuits the device. Making the copper conductor of small diameter in order to reduce its thermal conductance defeats the heat pump through ohmic heating. The solution to this problem is to provide a second pair of Peltier Effect junctions using a piece of n-type semiconductor. The conduction electrons in an n-type semiconductor are promoted to the conduction bands through thermal activation, and therefore carry heat just as holes do, but in the opposite direction. A complete thermoelectric module consists of two pairs of Peltier Effect junctions connected as shown in Figure C.2-2. As connected, the device is operating so that the copper bar connecting the two semiconductors is absorbing heat: it is called the cold plate. If the current is reversed, however, the direction of heat transport also reverses. Consequently, a thermoelectric device can be used for both heating and cooling depending upon the polarity of the power supply.

Thermoelectric modules may be ganged in series or in parallel (both electrically and thermally) in order to perform to a wide variety of specifications. Typical units are composed of many modules thermally in parallel and electrically in series so as to transport large quantities of heat over moderate temperature differences while operating at low current and moderate voltage. Thermoelectric cooling modules are remarkably inexpensive. For example, a 5 cm square module which will pump 30 watts of heat across a 20 deg C temperature change into a 35 deg C heat sink costs only about $50 in unit quantities.

In a production simulator employing thermal cuing of acceleration, a thermoelectric module could be mounted on the face of the ischial tuberosity bellows of the G-seat, inside a cutout in the seatpad. Analysis by Kron, Cardullo and Young (1980), who have studied this configuration, indicates that it can deliver appropriate temperature differences (about 1 degree C) to the skin overlying the ischial tuberosities. The air transported through the G-seat bellows will provide an adequate heat sink for the rejected heat in both the cooling and heating modes, while the thermal resistance of the pilot's clothing and the seat upholstery are not enough to prevent useful thermal contact between the device and the pilot's seat. The two main questions left unanswered by this analysis are those of the temperature control strategy and of the time delays due to thermal time constants of the equipment and the tissues of the pilot's buttocks.

Since skin temperature is highly variable, depending upon ambient conditions and pilot activity, it will be necessary to control the active temperature--the temperature of the contact side of the heat pump--by reference to real-time measurements of skin temperature in nearby, unmanipulated areas. In order to avoid instrumenting the pilot, since doing so would be impractical in a line simulator environment, reference skin temperature sensors should be placed on the seat surface below the pilot's thighs. Active temperature sensors must be placed directly on the faces of the heat pump modules. One objective of the experimental program would then be to determine an effective control strategy based on this configuration.

The most straightforward approach would simply be to command a specific temperature difference and have the temperature control loop track that commanded difference. It seems likely that such an approach might work, but there are refinements which do not require more hardware, and which may provide enhanced performance. Knowing the thermal resistance of the seatcover fabric and of the pilot's clothing, and computing the heat transport rate from the heat pump operating parameters, the manipulated pilot skin temperature can be computed. Since the seatpad is a much better thermal insulator than the seat cover and flightsuit, the reference sensors are in relatively good thermal contact with the pilot's skin in a low heat flux path and therefore give a reliable measurement of reference skin temperature. Knowing both the reference and manipulated skin temperatures, a temperature control strategy can be implemented using actual temperature change. The cuing algorithm can therefore be based on a parameter, skin temperature change, which is not affected by variables such as ambient temperature and pilot stress. The issue of time delay is much more problematic. An analysis such as that done by Kron, Cardullo and Young (1980) indicates that several seconds may be required to change skin temperature by an amount appropriate to cue high acceleration.

The time delay is due to a combination of the time constants to heat or cool the thermal mass of the heat pump and to heat or cool the tissues of the pilot's buttocks through the thermal resistances of the tissues, clothing, upholstery and heat pump cold plate. In the G-onset mode, this time delay is probably not consequential since the thermal stimulus is intended to provide persistence for other cues. In the G-relaxation mode, however, time delay in the removal of the thermal stimulus could result in false cuing. A major question for the experimental program will therefore be the extent to which the perceived time delay can be minimized. Since the skin is sensitive to very small temperature changes, and since it may well be sensitive to rate of change as well as absolute temperature, it is possible that the time delay associated with stimulus removal may not be a problem. One advantage of the thermoelectric device in this application is that it is polarity reversible, thus providing a transient response speedup capability when removing the stimulus. Only experimentation can adequately address this complex of issues, however.

An experimental hardware configuration poses no significant design challenges. Figure C.2-3 shows the configuration of a suitable experimental apparatus. The two thermoelectric modules are mounted on a plywood seat so as to lie directly below the subject's ischial tuberosities. Thermistor temperature probes are mounted on each heat pump face, on each heat pump heat exchanger, and on the seat surface just distal to the stimulated areas. A microcomputer monitors the active and reference temperatures as provided by the six probes, and computes the required drive voltage for the two heat pumps. The heat pumps are driven by two high-current programmable power supplies capable of bipolar output.

Since the thermal stimulus is not intended as a primary acceleration cue, it will be essential in conducting the perceptual portions of the experiments to provide a primary cue, preferably visual. The thermal cuing module could be constructed as a portable unit to be placed on the pilot's seat of a full flight simulator so that thermal cuing could be studied in the context of other motion cues and pilot workload.

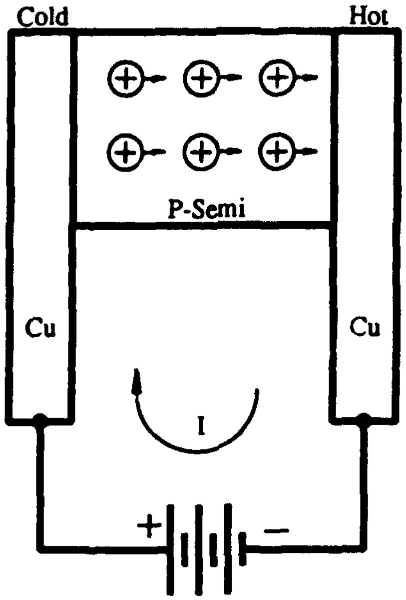


Figure C.2-1. Peltier Effect junction.

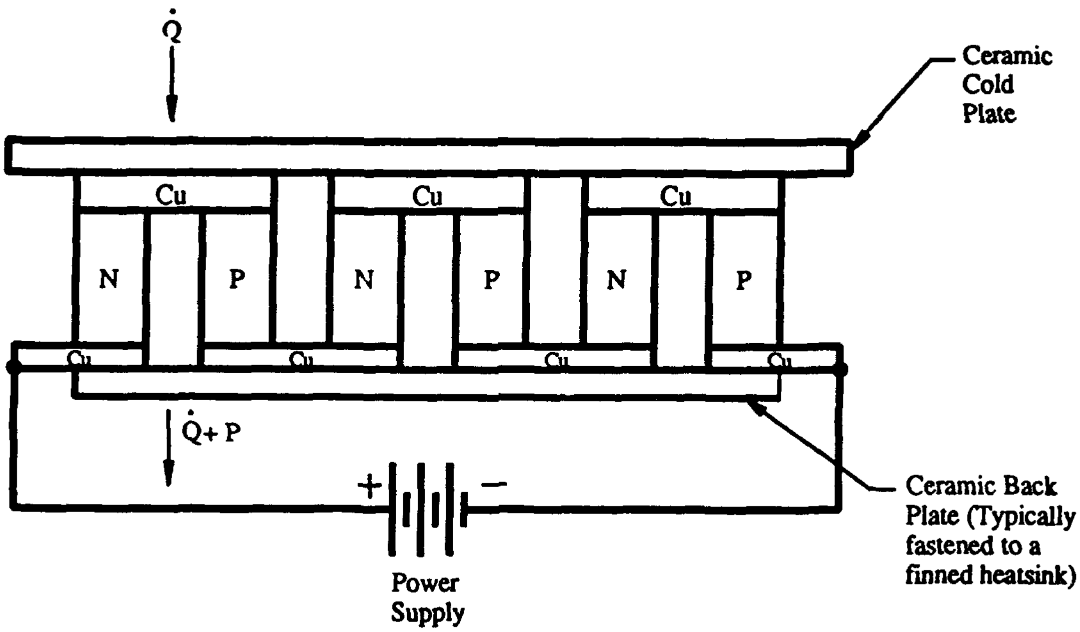


Figure C.2-2. Peltier Effect heating and cooling module.

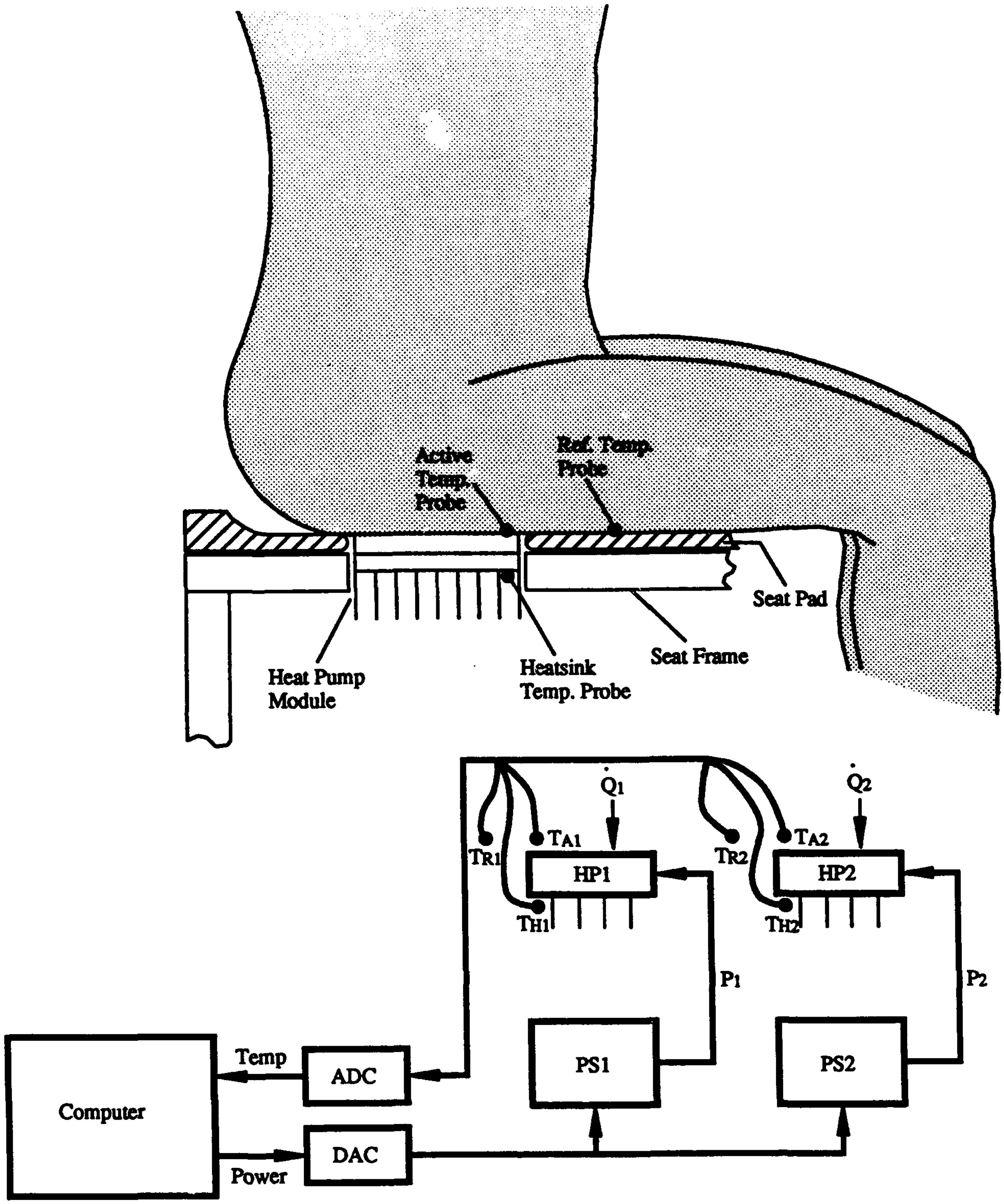


Figure C.2-3. Schematic diagram of a thermoelectric thermal cutaneous cuing module.

C.3 Experiments

C.3.1 Objectives

The ultimate objective of the thermal cuing experimental program is to develop a set of design guidelines for simulators using this technique of acceleration cuing. Due to the highly speculative nature of the technique, however, it will be appropriate to begin with fairly simple experiments designed to identify the recognizability of the cue, the sign and relative magnitude of the temperature shifts required, and the efficacy of the proposed temperature monitoring technique. Following these preliminaries, the program will proceed to an attempt to tease apart the perceptual effects of absolute temperature shift and the rate of that shift, the effects of adaptation (both for the thermal stimulus and the pressure stimulus), and to evaluate the usefulness of thermal cuing as an adjunct to a primary cue such as movement of the visual field. Finally, assuming these earlier efforts have been fruitful, the program will address the issue of a suitable cuing algorithm.

More specifically, the research effort must answer the following questions:

1. Can the proposed instrumentation adequately characterize the thermal stimulus?

   o Does a probe outside the clothing accurately measure skin temperature?

   o Can the heated or cooled skin temperature be measured indirectly by the proposed method?

   o Are the accuracy and stability of these measurements appropriate?

   o Do they provide useful information for controlling the stimulus?

2. What are the thresholds for sensitivity to the stimuli?

   o What is the nature of the adaptation process as it relates to the proposed cuing technique?

   o How does a heat stimulus differ from a cold stimulus? Which is appropriate for pressure cuing?

   o How does rate of temperature change affect the perception of the stimulus?

   o Can the dynamics of the percepts be described simply enough to allow for development of a

practical cuing algorithm?

3. What is an appropriate temperature control strategy?

   - Is latency a problem? If so, can it be overcome?

4. What is an appropriate cuing algorithm?

5. Does it work?

   - Does thermal stimulation enhance other motion cues?

   - If the thermal stimulation is not perceived as an enhancement to a pressure stimulus, can it effectively serve as an analog for pressure?

   - If thermal stimulation is used as an analog for pressure, how much training is required to make it seem natural?

C.3.2 Experimental Approach

An outline of the proposed experimental program follows.

1. Construct a preliminary apparatus consisting of one thermoelectric module, a manually controllable power supply and temperature monitoring equipment.

2. Make steady-state and dynamic measurements to verify the temperature monitoring procedures.

3. Make steady-state measurements to determine thresholds of perception of thermal stimulus.

4. Make dynamic temperature excursions to ascertain the characteristics of latency phenomena, both physical and perceptual.

5. If the results look promising, construct a breadboard cuing module which will allow automatic control of two thermoelectric modules. Include a suitable primary cuing device (such as a CRT visual display), or construct the device such that it can be installed in an operational simulator. Consider installing the thermoelectrics on the bellows of a G-seat or the tuberosity blocks of the Advanced Low Cost G-Cuing System.

6. Perform experiments aimed at determining the effectiveness of thermal stimulation as an acceleration cue.

7. Develop a suitable cuing algorithm.

APPENDIX D. Analysis of the Use of Torque Motors in a Direct Limb Loading Cuing Module

D.1 Introduction

Since acceleration causes a pilot's limbs to feel heavier, it is fairly obvious that one approach to simulating the limb loading effect is to use electric motors to exert forces directly on the pilot's limbs. For example, a pancake torque motor mounted on the pilot's elbow and with plastic arms sewed into the arms of the flight suit could apply a torque about the elbow which would result in the appropriate force on the pilot's forearm. The practicality of this concept depends upon the weight, size, and temperature rise characteristics of modern torque motors.

In flight, the pilot usually maintains his forearms roughly horizontal, so the g-force acting on the limb could act to produce a torque about the elbow. Conversely, a torque applied at the elbow will produce the appropriate g-force on the forearm. Figure D.1-1 shows the geometry. Assuming a forearm weight of about 5 pounds and a cg about 6 inches from the axis of the elbow joint, the g-induced torque is 30 lb-in/g or 2.5 lb-ft/g. Thus in an 8g maneuver, the pilot experiences an apparent forearm weight of 8g x 5 lb/g = 40 lb. This force can be applied in the simulation by a torque of 8g x 2.5 lb-ft/g = 20 lb-ft. Typical elbow flexion rates never exceed about 4 rad/sec with accelerations below about 16 rad/sec^2. The problem is to design an elbow loader which can simulate these effects while being carried on the pilot's elbow.

D.2 Engineering Analysis

For reasons of both safety and practicality, it seems reasonable to scale the force cue exerted on the pilot's arm. A torque motor which can deliver a full 20 lb-ft of torque could do a lot of damage to a pilot's arm in the event of a malfunction of its controller. Scaling of simulation cues is a somewhat arbitrary exercise, and one which is not without controversy, but for the purposes of this discussion, a 20% scaling seems a reasonable starting point. Although much less than the actual forces encountered in flight, g-forces scaled by 20% will certainly be discernable to the pilot, and will never be greater than what he could resist by muscular effort in the event of a malfunction. Assuming 20% scaling, the maximum torque required is 4 lb-ft. An Inland Motors model QT-3403 samarium-cobalt torque motor meets this requirement in a reasonably compact, frameless configuration. The relevant specifications of the motor are as follows:

Peak Torque	Tp	4	lb-ft
Friction Torque	Tf	0.16	lb-ft
Peak Power Input	Pp	126	W
Outside Diameter	OD	4.1	in
Inside Diameter	ID	2.0	in
Length	L	1.8	in
Weight	W	4	lb
No Load Speed	wNL	23	rad/sec
Rotor Inertia	Jm	9.8E-4	lb-ft-sec2
Temperature Rise	TPR	2	degC/W

The motor meets the torque requirement at 20% scaling. Maximum speed is 23 rad/sec, which is much greater than the required 4 rad/sec. The maximum acceleration is computed as

$$a = \frac{Tp - Tf}{Jm}$$

$$= \frac{4.0 lb\text{-}ft - 0.16 lb\text{-}ft}{9.8E - 4 lb\text{-}ft\text{-}sec^2}$$

$$= 3{,}900 rad/sec^2,$$

which is much greater than the required 16 rad/sec^2.

Temperature rise is a serious problem. At full torque, the temperature rise is

DT = TPR x Pp

= 2 degC/W x 126 W = 252 degC.

Of course, this temperature rise will occur only with 100% duty cycle at peak torque. Analysis of the Simulated Air Combat Maneuver (SACM), however, indicates an expected duty cycle of about 60%, resulting in a temperature rise of 151 degC. This is still unacceptable by a wide margin.

A second problematic issue is the size and weight of the motor. The size, although manageable, will certainly be noticeable--and even cumbersome--to the pilot. The weight, after addition of a motor frame, tachometer, load cell and power connections will probably be nearly five pounds, an unacceptable weight to add to the pilot's elbow. Given the temperature rise and the device weight problems, this approach to limb loading appears to be infeasible.

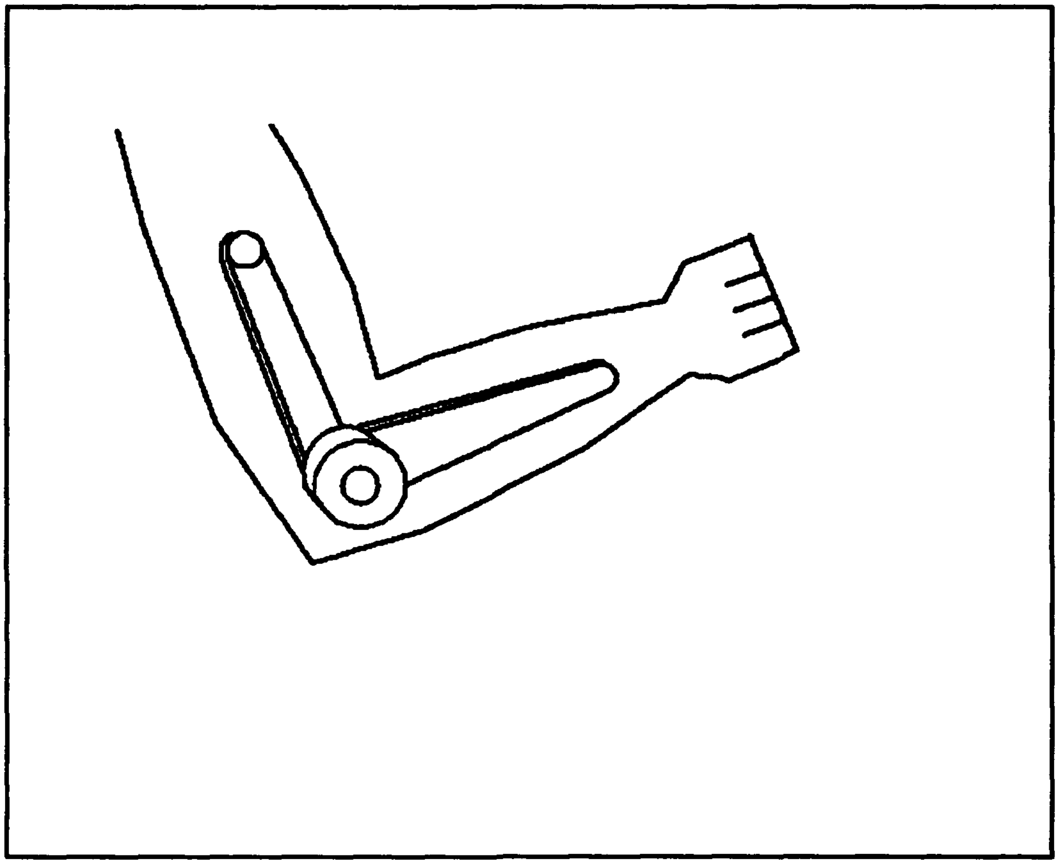


Figure D.1-1. Geometry of forearm loading.

APPENDIX E. An Experimental Variable Transmission Visor Cuing Module

E.1 General Considerations

The pacing technology for the variable transmission visor is the LCD itself. Helmet-mounted oculometers, although expensive, are now available with performance capabilities quite adequate for this application. If the computational system uses a lookup table technique or an edge computation technique to generate the mask shapes, the computational load will be within the capabilities of ordinary microprocessors. The LCD, however, must be of a multiplexed, matrix addressable design. This requirement places severe constraints on the speed of operation of which an LCD is capable. The current generation of matrix LCDs used in computer displays may be acceptable for the visor application, but this is an issue which only experimentation will resolve. The coming generation of matrix displays, which incorporate thin film transistor (TFT) integral switching, will solve the speed problem, but will most likely not be readily available for another year.

The general configuration of an LCD visor system is shown in Figure E.1-1. The host computer, after performing an analysis of the simulator state and its recent past history, commands a desired level of g-dimming to the Visor Controller, a microprocessor which is the computational heart of the system. Meanwhile the Helmet-Mounted Oculometer System (HMOS) has determined the instantaneous line of sight of the pilot's eye by examining the digitized image of the eye taken by a small CCD camera viewing the eye under IR illumination. Using these inputs, the Visor Controller computes the required state of each pixel in the LCD and commands the Visor Drive Electronics accordingly. The visor itself is a flat plate liquid crystal display, four inches high by eight inches wide, mounted on the flight helmet as close to the pilot's face as possible.

Normally, the LCD is clear, but when the host computer commands a certain level of G-dimming, the visor controller computes (or looks up) a pattern of darkened pixels which occult the desired amount of peripheral vision. Studies reported by Howard (1965) and Jaeger et al. (1964) have indicated the shape of the visual field under various amounts of G-dimming, and although the clear field is not circular, a proof-of-concept visor could use a circular pattern centered on a point midway between the optic disc and the fovea in each eye. Figure E.1-2 illustrates the arrangement. In an advanced development device the appropriate shapes could be stored in the memory of the Visor Controller.

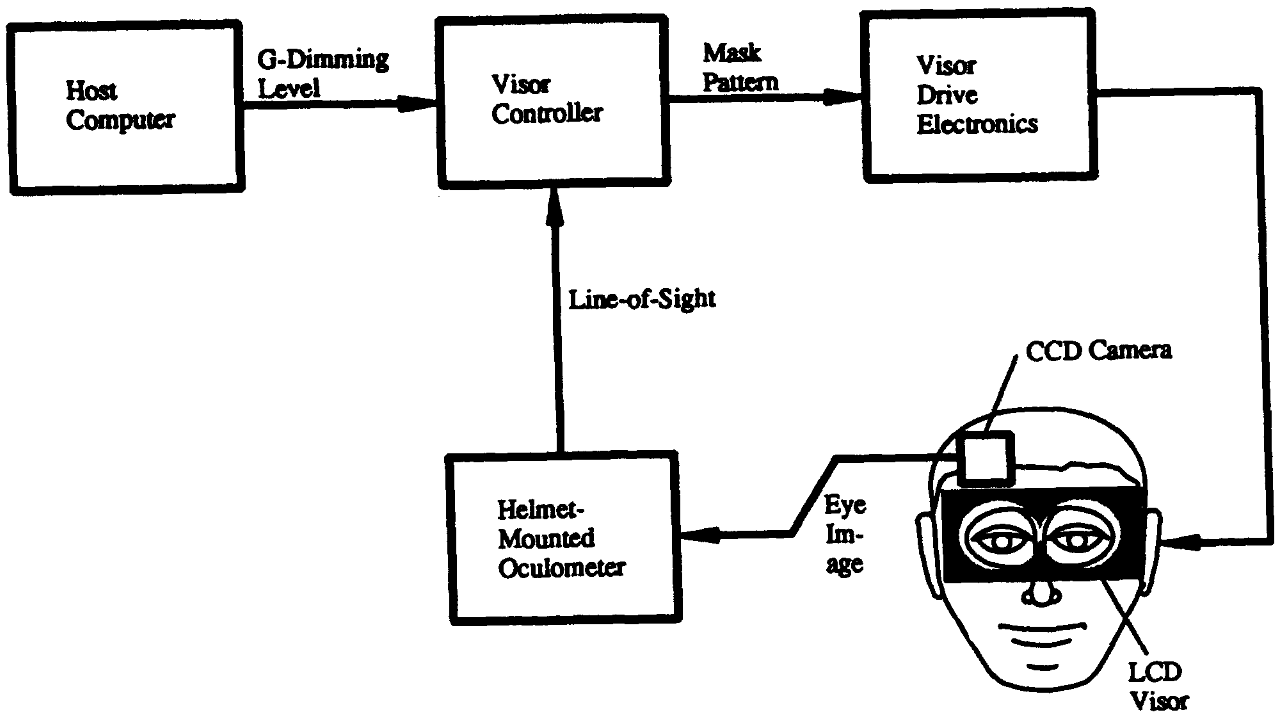


Figure E.1-1. System diagram of a variable transmission visor cuing module.

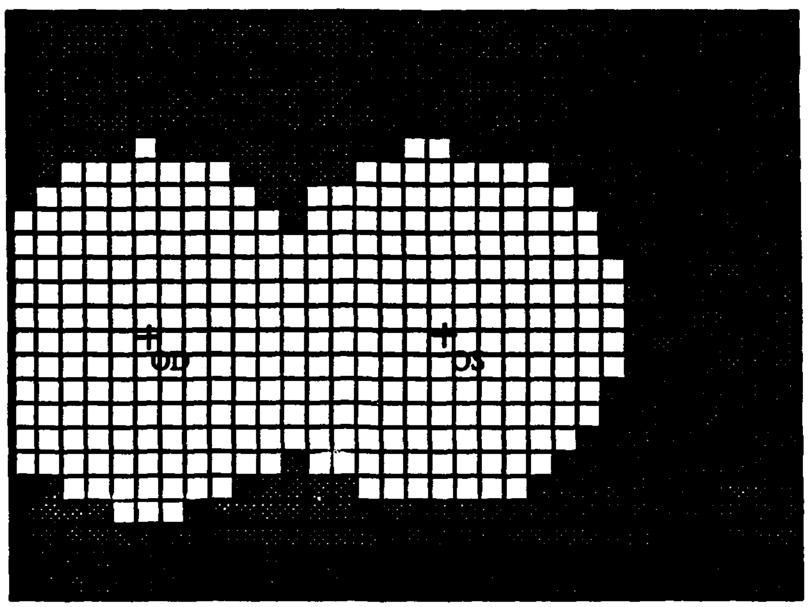


Figure E.1-2. Visor pixel matrix showing sample occultation mask.

E.2 LCD Selection

A typical LCD used for graphic display consists of a thin layer of twisted nematic liquid crystal sandwiched between two plastic or glass sheets onto which a pattern of transparent conductors has been deposited. This assembly is placed between crossed polarizing films and backed by a reflective coating. Figure E.2-1 shows the configuration. The front polarizer polarizes incident light. As the polarized light passes through the liquid crystal, the plane of polarization is rotated through 90 degrees so that it passes unattenuated through the back polarizer, and is reflected back through the liquid crystal. The crystal again rotates the plane of polarization so that it may pass through the front polarizer unattenuated and out to the observer. Assuming that the incident light is randomly polarized, the total loss through the system is just over 50%, almost entirely because of the attenuation at the first polarizer. Thus the system has a reflectance of just under 50%. Now when a voltage is applied across the electrodes, thus imposing an electric field on the liquid crystal, the crystal structure is altered so that its optical activity disappears. The result is that the crystal does not rotate the plane of polarization of the light passing through it and all the light is absorbed at the back polarizer. Thus when the voltage is applied, the system has a very low reflectance. Since the polarity of the applied voltage is immaterial, LCDs typically use an AC square wave in order to prevent electrolytic effects within the liquid crystal. This type of reflective display is the most common, but it is actually a transmissive light modulator with a reflector behind it. Without the reflector the system operates in a transmissive mode with a maximum transmittance of about 45% and a minimum of about 1%. Transmission mode LCDs are less common than reflection mode LCDs but they are widely used in backlighted information display applications.

The pattern of transparent electrodes determines the pattern of imagery the LCD can display. Many special purpose displays have various symbols and icons deposited on one side and a continuous ground plane on the other. Control and drive circuitry simply selects which elements are to be activated and switches drive voltage to the proper electrodes. General purpose and graphic displays, which can be called upon to display arbitrary images, require a matrix of individually addressable pixels. This configuration is accomplished by depositing the transparent electrodes in a pattern of horizontal stripes (rows) on the top glass and a pattern of vertical stripes (columns) on the back glass. The geometrical intersection of a row electrode and a column electrode is a square pixel. It can be activated by applying drive voltage to the row and column electrodes which define it.

This arrangement allows for the individual activation of any

pixel, but, of course, only one pixel at a time may be activated. In order to build up an image composed of many pixels, the display must be multiplexed. In a typical multiplex arrangement, the drive circuit first connects the first row and then sequentially connects each of the column electrodes, energizing those electrode pairs for which the associated pixel is to be activated. The driver then moves to the next row and repeats the process, scanning across the columns. When the entire display has been scanned, the process repeats. By scanning rapidly, the display system produces the visual illusion of a continuous image in precisely the same manner as a television display. The problem with multiplexing an LCD is that as the number of pixels increases, the amount of time that each pixel is activated decreases proportionally. Since the rise time for change of state of a typical twisted nematic liquid crystal is on the order of 200 milliseconds, an extremely short activation time will not produce full activation, thus reducing contrast. A rapid scanning rate, however, can significantly improve performance.

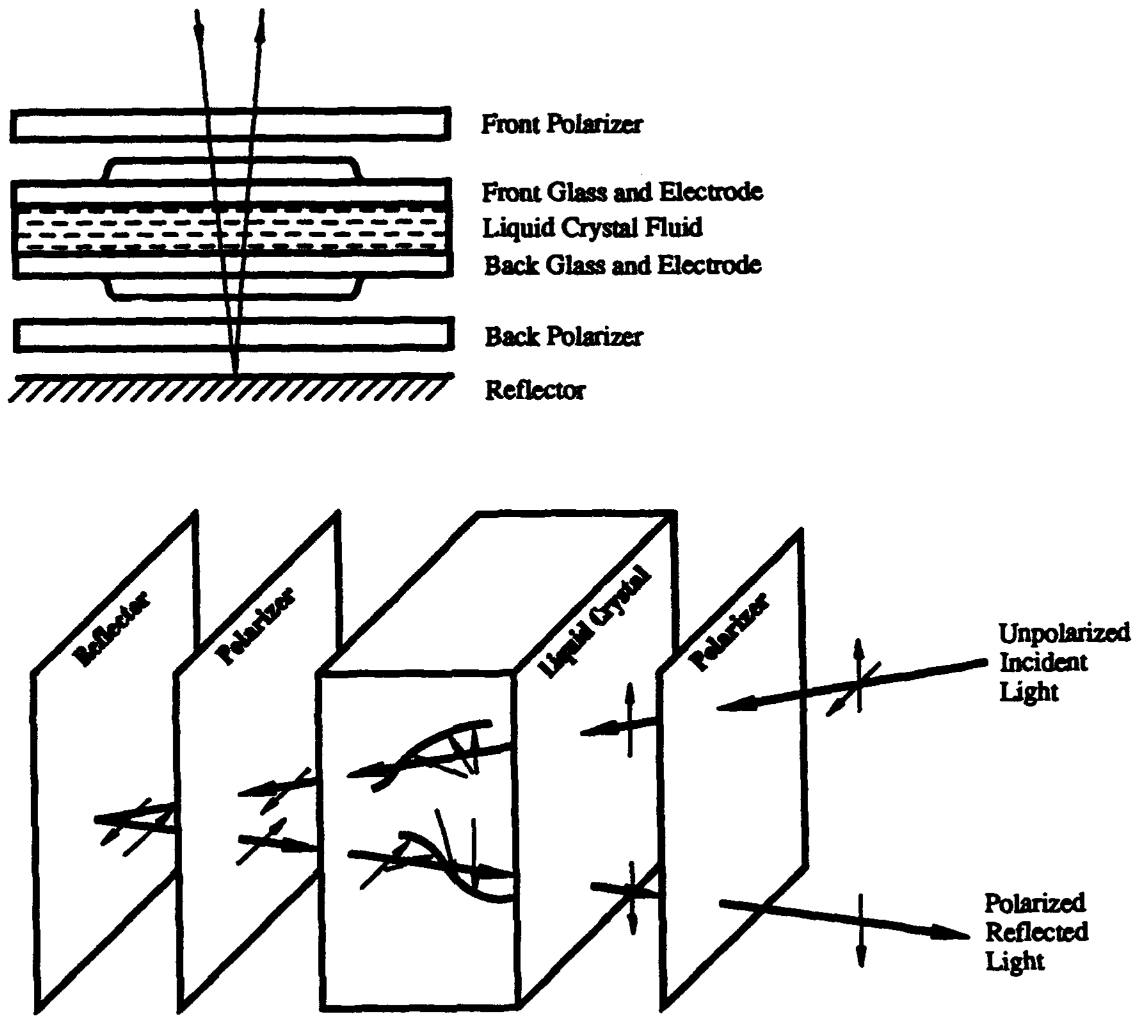
A typical multiplexed, matrix addressable computer display might have 400 rows and 640 columns for a total of 256,000 pixels. Dividing the display in half for simultaneous drive, each active area contains 200 x 640 pixels or 128,000 pixels. With a scan rate of 60 Hz (so as to conform with video standards), the dwell time on each pixel is only 130 nanoseconds. This time is not nearly enough to fully activate the liquid crystal, but with a 60 Hz repetition rate, the device can achieve a contrast ratio of about 5. Although the repetition rate for driving the scan is 60 Hz, the response time of the liquid crystal is still more than 200 milliseconds, so a complete rewrite of the screen will not be visible for that amount of time.

For application in a variable transmission visor, an LCD such as the device described above has two major drawbacks. First is that, because of the requirement for polarizers, the best clear-mode transmittance possible is about 45%. Looking through the device will be similar to looking through polarizing sunglasses. The second major drawback is the response time. The time required for changes in the G-dimming effect are quite large compared to the time constant of the LCD, so that is not a problem; but the clear area must be repositioned rapidly following a sudden eye movement. After a saccade, the visor must reposition the clear area of the visor within the saccadic suppression time. Saccadic suppression is somewhat variable, and a precise figure applicable to this particular scenario is not available. It is possible that experimentation could show that the response time of the current generation of LCDs is adequate in this application, but the accepted values of saccadic suppression of 60 to 180 ms are clearly much shorter than the LCD response time.

As long as LCDs make use of the optical activity of liquid

crystals, polarizers will be required and the maximum theoretical clear-mode transmittance will never be better than 50%. Guest-host or dichroic LCDs do not require polarizers, but they are not effective over all colors simultaneously and have clear-mode transmittances even lower than do the twisted nematic types. Barring an unanticipated breakthrough in LCD technology, the maximum transmittance to be expected from a liquid crystal visor is about 45%.

As a result of the strong desire within the LCD industry to produce LCD television screens, much research effort has been directed at the problems of response time and contrast in a multiplexed display. The solution to this problem lies in the use of integral switching provided by transparent thin film transistors deposited directly on the glass at each pixel. Each transistor switch is capable of holding the voltage of a charged capacitor across its associated pixel throughout the scanning cycle, thus eliminating the dead time between cycles. The transistors are addressed in a multiplex fashion and either switched on or off as required. This type of display will be more suitable for the visor application, but engineering samples will not be available in suitable sizes for at least another six months. Because the visor will be placed well within the pilot's visual nearpoint, the pixel pitch need not be greater than about 10 per inch. A 4 inch by 8 inch visor would therefore have 40 x 80 = 3,200 pixels. This is many fewer pixels than are provided on a typical off-the-shelf computer display and may therefore provide better performance. Custom LCD manufacturers indicate, however, that a prototype package of a single display and associated drive electronics would cost between $10,000 and $20,000. Production units, on the other hand, would be on the order of a few hundred dollars each.



When the LC is energized, no rotation of polarization takes place and the light is absorbed at the back polarizer.

Figure E.2-1. Operation of a liquid crystal display element.

E.3 Experiments

The objectives of early experimentation must be to determine whether the transparency and speed of the LCD are adequate for the visor application. Preliminary experiments can be performed without an oculometer--or even a complex drive algorithm--by having the subject saccade on a command from one predetermined fixation point to another while simultaneously commanding the visor clear area to move the same amount. If the subject can easily find fixation points outside his original field of view, then the speed of the device may be considered adequate. In performing this experiment, a delay representing the oculometer transport delay must also be included.

A simple experiment of this sort is a first step toward evaluating the effectiveness of the technology and the concept. A full evaluation of the usefulness of the system will require implementation of the complete system--including an oculometer--in a simulator environment where the subjects can exercise the device while performing realistic maneuvers. The experiments must be designed to answer several questions:

1. Does the relatively low clear mode transmittance adversely affect performance in the low-G regime?

2. Does the peripheral vision loss provided by the visor perceptually correspond to the actual sensations induced by acceleration?

3. Does the visor provide a useable cue for G-dimming?

4. What is the appropriate cuing algorithm?

5. Can the hardware be made compatible with the simulator environment, particularly the flight helmet?

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